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An analysis of the kill chain for time critical strike

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THESIS

AN ANALYSIS OF THE KILL CHAIN FOR TIME-CRITICAL STRIKE

by

William K. Brickner

June 2005

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AN ANALYSIS OF THE KILL CHAIN FOR TIME CRITICAL STRIKE

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ABSTRACT

Because of their limited window of vulnerability, the detection and destruction of Time-Critical Targets (TCTs) has been a significant challenge for our military forces. The Naval Air Systems Command (NAVAIR) has investigated a future time-critical strike (TCS) architecture and concept of operations (CONOPS) in order to explore the effectiveness of high-speed weapons against TCTs. NAVAIR has represented the network-centric architecture and CONOPS in a simulation model. This thesis extends NAVAIR's work by developing flexible simulation models and exploring the effects that alternative CONOPS and technology enhancements may have on high-speed weapon requirements and overall system performance against TCTs. The TCTs are a single wave of theater ballistic missile (TBM) transporter-erector-launchers (TELs) appearing over a short time interval. The wave of TBM TELS can saturate the command and control architectures considered. The CONOPS is to use weapons with the shortest fly-out times first. For the architecture and alternative CONOPS explored, it is difficult to improve upon the performance of the baseline TCS system developed by NAVAIR.

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LIST OF ACRONYMS

C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CAP	Combat Air Patrol
CONOPS	Concept of Operations
DPPDB	Digital Point Positioning Database
FCFS	First-Come, First-Served
GMTI	Ground Moving Target Indicator
GPS	Global Positioning System
ISR	Intelligence, Surveillance, Reconnaissance
LIFO	Last-In, First-Out
MOE	Measure of Effectiveness
NAWCWD	Naval Air Warfare Center, Weapons Division
NCW	Network-Centric Warfare
Pk	Probability of Kill
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications
TAI	Target Area of Interest
TBM	Theater Ballistic Missile
TBMD	Theater Ballistic Missile Defense
TCT	Time-Critical Target
TEL	Transporter-Erector-Launcher
TLE	Target Location Error
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
WEZ	Weapon Engagement Zone

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EXECUTIVE SUMMARY

Because of their limited window of vulnerability, the detection and destruction of time-critical targets (TCTs) has proved to be a significant challenge for our military forces throughout the years. Advances in information and networking technology, along with increased sensor capabilities aim to reduce the time required to neutralize potential threats. However, these improvements may not be enough, or prove to be too costly, to effectively destroy many time-critical targets.

In an effort to explore methods for reducing the time required to prosecute TCTs, the Naval Air Systems Command (NAVAIR) has investigated the utility of high-speed weapons in the context of an overall time-critical strike (TCS) architecture and concept of operations (CONOPS). The primary objective of NAVAIR's work is to identify weapon speed and range requirements that are compatible with other systems in the TCS architecture, which may enable the successful prosecution of TCTs.

An important part of the NAVAIR high-speed weapons study is to investigate a TCS architecture and CONOPS for a system in the 2015 to 2020 timeframe. This system provides a framework within which to explore the effectiveness of high-speed weapons against TBM TEL threats. Presumably, there are other missions for high-speed weapons, but they are not addressed by the NAVAIR study or this thesis.

Along with high-speed weapons, the TCS architecture investigated by NAVAIR consists of three additional major sub-systems; a Ground Moving Target Indicator (GMTI) radar to track moving TELs, a Synthetic Aperture Radar (SAR) to form high-resolution imagery of stopped TELs, and the Digital Point Positioning Database (DPPDB) from which an image analyst derives target coordinates of stopped TELs. The TCS architecture also includes centralized Command and Control (C^2).

To conduct analysis, NAVAIR represents a Network-Centric Warfare (NCW)-based architecture and CONOPS in a TCS simulation model (Ryan Gillespie, NAWCWD, Code 4J2100D) using the *Extend* software package. The TCS *Extend* model is a system of first-come, first-served (FCFS) queues that selects the closest shooter platform with available weapons to engage each TCT as it appears in a simulated campaign.

This thesis supports NAVAIR's effort through the development of smaller, more flexible simulation models than that currently in use. The models developed for this thesis are used to determine if alternative operating procedures or technological improvements within the TCS architecture, along with Mach 4 high-speed weapons may increase the likelihood of successful TCS missions.

The specific TCTs addressed in this thesis are mobile Theater Ballistic Missile (TBM) Transporter-Erector-Launchers (TELs). TBM TELs are capable of launching short to long-range ballistic missiles armed with conventional or nuclear warheads. They hide, undetected, in obscure locations until moving to their areas of operation. Upon arrival at these areas, the TBM TELs become stationary while launch preparations are made and missiles are fired. After missile launch, the TELs remain stationary while they are prepared for transit back to their hide locations. The amount of time that a TBM TEL remains stationary is referred to as its *dwell time*. Dwell times are random variables and have different distributions for different TEL types. Because of classification issues, this thesis uses surrogate TELs having mean dwell times based on time-critical targeting objectives (see Figure 7). Although TBM TELs are tracked while in transit, this thesis assumes that they are only vulnerable to attack during their dwell times. If a TEL completes its dwell time (starts moving again after missile launch), it is assumed to be lost. It is also assumed that an engagement of one TEL does not affect the behavior of the other TELS; they act independently, statistically speaking.

The Red attack scenario developed for this thesis is a single wave of TBM TELs. The scenario considers two TBM TEL employment tactics for each attack wave; coordinated TBM launches and coordinated TEL stops. For the coordinated TBM launch tactic, all TELs in an attack wave launch a single TBM within a five-minute time interval. For the coordinated TEL stops tactic, all TELs stop within a five-minute time interval. Regardless of the employment tactic, the number of TELS in a single wave can be large enough to saturate the C^2 architecture. The Blue CONOPS considered is to fire the weapon with the smallest fly-out time to engage a TEL. For the scenario, architecture and CONOPS explored, the results of the thesis suggest that the most promising modifications are: (a) the development of a Track-While-Scan GMTI and SAR sensor that is capable of tracking moving targets and forming SAR images simultaneously, and (b) the ability to update the status of TELs (stationary or moving) currently in the system and remove those TELs from further processing that have left their TBM launch sites before the system can engage them. Neither the NAVAIR architecture nor any of the potential modifications explored in this thesis enable the investigated TCS system to, successfully and consistently, engage TELs having mean dwell times of 10 minutes. This is a strong statement; therefore, it is important to note that the system may be more effective against short-dwell TELs under a different set of assumptions (e.g. faster weapons, shorter shooter-to-target ranges, etc.)

Although not directly addressed in this thesis, the results imply that the system is very sensitive to TEL decoys for a large wave launch. This is because the mean cumulative processing delays, excluding weapon time of flight, exceed the mean dwell times for TELs stopping in the latter stage of a large launch wave.

Alternative queueing disciplines such as LIFO and priority are ineffective for all coordinated TBM launch cases because the TELs tend to stop in nearly descending order of their dwell times, regardless of TEL type. As a result, the system also tends to process the TELs in descending order of dwell time. This is an artifact of the representation of the coordinated TBM launch arrival process.

I. INTRODUCTION

Because of their limited window of vulnerability, the detection and destruction of time-critical targets (TCTs) such as mobile theater ballistic missile (TBM) transporter erector launchers (TELs) has proved to be a significant challenge for our military forces throughout the years. Analyses of Desert Storm operations concluded that the U.S.-led coalition was not able to confirm the destruction of a single Iraqi mobile SCUD launcher during the entire operation. Since then, advances in information and networking technology along with increased sensor capability have enabled the emergence of a concept described as Network-Centric Warfare (NCW) that is expected to revolutionize the way the military conducts these strikes, as well as all other military operations. The time-critical strike (TCS) goal of NCW is to decrease the execution timeline of the kill chain; that is, to reduce the time required to detect, decide, engage and assess TCTs such as TBM TELs. Unmanned Aerial Vehicle (UAV) Intelligence, Surveillance and Reconnaissance (ISR) platforms carrying advanced sensors, and improvements to the command, control and communications (C^3) architecture should significantly reduce the kill chain timeline. However, these improvements may not be enough, or prove to be too costly, to effectively destroy TELs. Therefore, there is a need to be able to evaluate the capability of potential TCS architectures to achieve success in the TCS mission.

A. BACKGROUND

The Naval Air Systems Command (NAVAIR) has been involved with high-speed missile studies for several years. Most recently, OPNAV N70 (Warfare Integration) tasked NAVAIR to investigate the utility of high-speed strike weapons. The first objective of this Time-Critical Strike and High-Speed Weapons study is to determine the composition and implementation timeframe of a Network-Centric Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) architecture (FORCEnet) and Concept of Operations (CONOPS) that may be able to support the employment of conceptual high-speed strike weapons. The second objective is to use this architecture as a framework in which to investigate whether the use of high-speed strike weapons may increase the likelihood of a successful TCS mission and, if so, to recommend weapon speed and range requirements.

To conduct analysis, NAVAIR implements the NCW-based architecture in a campaign-level TCS simulation model (Ryan Gillespie, NAWCWD, Code 4J2100D) using the *Extend* software package (reference 3). Initial versions of NAVAIR TCS *Extend* model measure the effectiveness of a high-speed weapon by varying its speed and range within this static architecture and fixed set of CONOPS. This approach, however, is only one potential solution for one portion of the kill chain. A more comprehensive analysis of all elements of the kill chain is necessary to determine a set of systems, technologies, and CONOPS needed to reduce the total time required to prosecute TCTs and increase the likelihood of successful TCS missions.

B. OBJECTIVE AND SCOPE OF THIS THESIS

The purpose of this thesis is to support the Time-Critical Strike and High-Speed Weapons study by developing flexible simulation models with which to explore the effects of alternative operating procedures and technological improvements within the TCS architecture partially investigated by NAVAIR on the TCS mission. The specific targets addressed in this thesis are TBM TELs. This research also evaluates the architecture's sensitivity to assumed TEL arrival processes and dwell time distributions.

The scope of this thesis does not include changing the architecture's composition of systems or addressing battle damage assessment (BDA). This thesis does not address weapon accuracy or lethality; both are assumed perfect. Instead, it is concerned with whether or not a weapon's time-on-target (TOT) is less than a TEL's dwell time.

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II. TCS ARCHITECTURE AND CONOPS

A. THE KILL CHAIN

The TCS kill chain consists of six processes. They are find, fix, track, target, engage, and assess (reference 5). Figure 1 illustrates the blocks in the kill chain and the end-to-end set of TCS timeline goals.

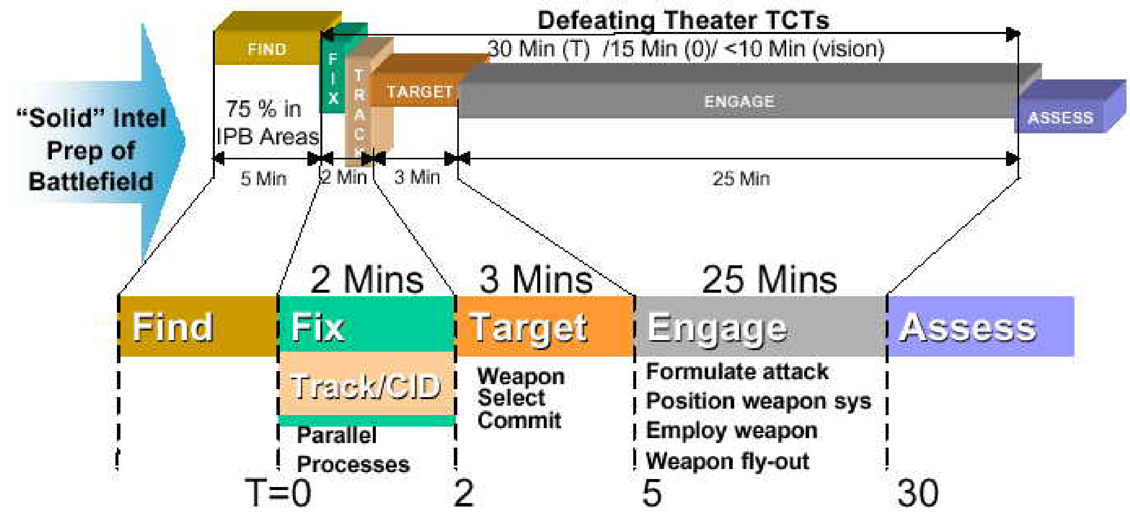

FIGURE 1. KILL CHAIN ELEMENTS AND ASSOCIATED TCS TIMELINE GOALS (DERIVED FROM REFERENCE 5)

B. INTRODUCTION TO MAJOR SUB-SYSTEMS

The TCS system architecture investigated by NAVAIR has centralized Command and Control (C^2) and consists of four major sub-systems that execute the phases of the kill chain shown in Figure 1: (a) a Ground Moving Target Indicator (GMTI) radar mounted on a high-altitude, long-endurance unmanned combat aerial vehicle (UCAV) that finds and tracks targets; (b) a Synthetic Aperture Radar (SAR), mounted on the same UCAV platform, that performs targeting and assessment tasks; (c) the digital point-positioning database (DPPDB) that is used to fix, or mensurate, weapon aimpoints; and (d) shooter platforms that engage targets with high-speed weapons. The assess portion of the kill chain is not addressed in this thesis. The following sub-sections give a brief overview for each of these systems.

1. Ground Moving Target Indicator (GMTI) Radar

GMTI is a day or night, all-weather radar capable of tracking multiple moving targets over a large area in near-real time. It has an imaging capability; however, the resolution is insufficient for identifying targets. GMTI operates continuously and is able to update target movement according to the frequency with which the radar beam passes over a given area. This frequency is referred to as the *cycle length* or *revisit rate* of the GMTI radar. If a target stops between radar visits, the GMTI cannot distinguish it from other stationary objects in the background and the GMTI loses the track when it returns to the area.

2. Synthetic Aperture Radar (SAR)

SAR is also a day or night, all-weather radar; however, unlike GMTI, it is able to form high-resolution images that can be used to identify stationary targets. The radar is able to obtain this resolution by taking sequential measurements as the sensor platform moves along a linear path. This has the effect of virtually increasing the radar's antenna length by the distance traveled while taking measurements. The time to form SAR images is a function of the sensor platform's speed and range from the target. This delay is typically around 15 to 20 seconds for the NAVAIR CONOPS.

Because of its high-resolution imaging capability against stationary targets, a UCAV with a GMTI/SAR sensor suite payload that is capable of tracking and locating TCTs is a promising and complementary combination.

3. Digital Point-Positioning Database (DPPDB)

GMTI and SAR radar Target Location Errors (TLE) are too large to derive coordinates for precision global positioning system (GPS) guided weapons. In order to reduce these TLEs, improvements need to be made in either the uncertainties of the sensor location and pointing angles and/or the accuracy of the digital elevation models (DEM) that represent the topographic surface. Registering imagery to the DPPDB improves SAR TLEs by reducing these uncertainties.

The *DPPDB* is a stereo-image based product developed by the National Imagery and Mapping Agency (NIMA). The composition of the DPPDB consists of exploitation support data, a digital reference graphic, and compressed stereo imagery. The database is usually parsed into 60 by 60 nautical mile rectangles. The DPPDB is attractive because of its availability and accuracy.

4. High-Speed Weapons

The notional weapons represented in this thesis assume a maximum range of 500 nautical miles and an average speed of Mach 4 (3,840 ft/sec). They are GPS-guided and have unitary warheads that are assumed to have sufficient lethality to kill a single TEL based on the precision coordinates extracted from the DPPDB. Both airborne and surface shooter platforms employ the weapons. This thesis does not explore the effects of possible GPS jamming on weapon delivery accuracy.

C. SCENARIO AND ASSUMPTIONS

The scenario adopted in this thesis is a single wave of many TBM TELs that either stop or launch TBMs within a five-minute time interval. The size of the launch wave ranges from 15 to 45 same-type TELs. Each TEL in the launch wave follows a similar pattern of behavior: emerge from a hide site, transit to launch site, prepare for launch, fire a single missile, prepare for departure, and transit from the launch site back to a hide site. A TEL is stationary from the time it begins launch preparations until its departure procedures are complete. This time interval is called the TEL’s *dwell time*. Each TEL is vulnerable to attack only during its dwell time. A TEL is said to be *lost* if it begins transiting back to its hide spot before it has been engaged by a weapon.

TBM TEL launch waves are employed in one of two ways; coordinated TBM launches or coordinated TEL stops. The former attempts to synchronize TBM launches in order to saturate theater ballistic missile defense (TBMD) systems, while the latter attempts to synchronize the times at which TELs arrive at their launch locations in order to induce congestion in the TCS system architecture.

This scenario assumes perfect intelligence preparation of the battlefield (IPB). Therefore, the general TBM launch locations are known and the ISR asset is optimally pre-positioned in the theater. This insures that all of the launch locations are covered. Consequently, the GMTI radar is tracking all TELs in a launch wave before they stop to prepare for TBM launch.

Shooter platforms situated at fixed locations are available to engage TELs with Mach 4 weapons after C4ISR processing is complete. One high altitude, long endurance UCAV platform whose payload consists of two high-speed weapons and the GMTI/SAR ISR sensor suite is loitering at the first shooter location that is 50 nmi from the suspected TBM launch area. Although anti-air defenses are not addressed in this thesis, the UCAV is assumed survivable in the presence of any surface-to-air missile (SAM) and/or anti-aircraft artillery (AAA) sites. The second shooter location is a combat air patrol (CAP) established 200 nmi from the TBM launch area. This distance ensures that each aircraft is out of any potential SAM weapon engagement zones (WEZ). The CAP consists of four F/A-18 E/F aircraft, each carrying a payload of four high-speed weapons (16 weapons total). The last shooter is a surface ship located 300 nmi behind the CAP, or 500 nmi from the TBM launch area. Shooter platforms are selected to engage TELs based on their range to the TBM launch area and whether or not they have weapons available.

D. BASELINE BLUE CONOPS

A UCAV tracks and detects TELs. It is equipped with a payload of two high-speed weapons and a GMTI and SAR ISR sensor suite. Although the radars work together in the detection process, there is no current capability to operate both simultaneously on the same platform.

GMTI is the UCAV’s default ISR mode. While in this mode, the ground controller updates tracks on all TELs within the sensor’s coverage area every two minutes, the length of a complete GMTI cycle. If any tracked TELs are not moving when the GMTI radar beam passes over their projected locations, the TEL tracks are lost and held in a queue. Once the initial tracks are lost, the ground controller performs one additional GMTI scan to verify any stopped targets in the queue have not started moving again. If reacquisition of a TEL fails, the ground controller completes the remainder of the GMTI scan before cueing the SAR. While in SAR mode, the ground controller forms high-resolution spot images for all confirmed stopped TELs in the queue and passes the imagery to the command center for further processing via a satellite communications (SATCOM) data link. The ground controller then switches the sensor platform back to GMTI mode for detection and tracking after forming SAR spot images for all targets in the SAR queue.

The analysis of SAR imagery is a two-stage sequential process consisting of searching the image for a target and then identifying the target as a threat. For the purposes of this thesis, the analyst correctly locates and identifies the TEL in each SAR image with probability 1. There is no misclassification matrix.

After decompression, the images enter a first-come, first-served (FCFS) queue where they await processing by an analyst. The image analyst examines each SAR image individually, first searching for the presence of a target and then identifying the target as a TEL. Once identified, the analyst simultaneously passes the target information to the command center for strike approval and registration to the DPPDB.

During the mensuration process, each target-image pair is registered to the DPPDB for detailed coordinate derivation. While the targets are being registered, the command center approves whether or not to strike based on the findings of the image analyst and the current estimate of the situation. Engagement begins after the coordinates are obtained and the command center approves the strike. The shooter platform closest to the TEL that has an available weapon always engages the TEL. If the TEL has not completed its dwell time before the weapon arrives, the engagement is a success. For the baseline CONOPS, it is not known whether a TEL has completed its dwell time. Therefore, a single weapon is fired at every TEL in a launch wave.

E. ALTERNATIVE CONOPS AND TRACK-WHILE-SCAN CAPABILITY

This section describes the alternative CONOPS and the track-while-scan capability explored in this thesis.

1. Track-While-Scan ISR Capability

There is no current capability to operate the ISR platform's GMTI and SAR radars simultaneously. Therefore, in order to form SAR imagery for stopped TELs, the ground controller must switch the ISR platform from GMTI to SAR mode at the end of all completed GMTI scan cycles where TELs are present in the SAR queue. No updates on moving targets can be performed during the formation of these SAR images. Consequently, the detection delay of stopped TELs during the formation of SAR imagery increases by the amount of time until the ground controller switches back to GMTI mode. This delay is equal to the number of TELs in the SAR queue multiplied by the time to form each SAR spot image.

A possible system enhancement is to develop a track-while-scan capability that enables ground controllers to operate the ISR platform's GMTI and SAR radars simultaneously. As a result, the ground controller is able to update GMTI radar tracks continuously while forming SAR radar spot images as necessary. Unlike the baseline, the track-while-scan CONOPS allows the ground controller to put stopped TELs in the SAR queue for spot imaging at any time during a GMTI cycle. However, these CONOPS still require the TEL to be stationary for two consecutive passes of the GMTI radar beam before it can enter the SAR queue.

2. Updating

Under the baseline CONOPS, a shooter platform engages every detected TEL that enters the kill chain process. However, because of processing delays or short dwell times, some TELs may leave their launch sites before a shooter platform engages them. This imposes a risk that time will be spent servicing TELs that cannot be killed. These TELs are effectively decoys that waste missiles and may induce unnecessary processing delays on other TELs. Updating the status of stopped TELs may eliminate some of these delays and wasted shots by aborting further processing of those TELs that have completed their dwell times before a shooter platform engages them.

This thesis will consider a variation of the baseline CONOPS in which each TEL that has not been engaged before the end of its dwell time may receive one update regarding its movement status. The updating process begins the first time the GMTI radar beam passes over the TEL’s launch location after the TEL starts moving back to its hide site. It is assumed that the ground control station immediately and correctly correlates the position of this new track with the lost tracks of previously detected TELs. The ground controller then requests a second SAR spot image of the TEL’s launch location according to the baseline CONOPS. That is, the image request enters the FCFS SAR queue. No confirming GMTI scan is required. Further processing of the TEL is aborted with no delay after the image analyst concludes that the new track is a previously detected TEL and a shooter platform has not yet engaged it with a high-speed weapon. The time required for the image analyst to analyze the updated imagery is distributed the same as the time to search the initial images.

3. Alternative Queueing Disciplines

The baseline CONOPS assumes that all systems in the TCS architecture process TELs on a FCFS basis. This is not a potential problem if all TELs share the same dwell time. Launch waves, however, generally consist of several different TEL types. There is also variability among TEL dwell times. Therefore, the order in which these TELs are processed may affect overall system performance. For example, processing delays due to congestion may degrade the TCS system’s effectiveness, or render it useless, against short-dwell TELs. In this section we describe CONOPS involving alternative queueing disciplines that are considered in this thesis.

a. Last-in, First Out (LIFO)

The LIFO queueing discipline applies to the order in which the image analyst processes SAR imagery. The most recent arrival to the analyst's queue is always serviced first. Other queues in the system remain FCFS. The LIFO queueing discipline may enable the system to successfully engage TELs that may be lost because of congestion in the image analyst's queue.

b. Prioritizing TELs by Type

This queueing discipline prioritizes TELs according to their mean dwell times. For example, engaging medium-dwell TELs first may be advantageous if the system comfortably engages long-dwell TELs, but is ineffective against short-dwell TELs. Prioritization requires that TEL types are known and it applies to all queues in the TCS system.

III. SIMULATION METHODOLOGY

A. THE *EXTEND* SOFTWARE PACKAGE

1. Introduction

The *Extend* software package is a visual environment in which users can create discrete and/or continuous simulation models. *Extend* provides modelers with many pre-defined functional blocks that are connected together in order to represent a system or process. *Extend* generates objects such as TELs and passes them through a model. In most cases, each block delays, modifies, services, and/or routes objects. If the default libraries do not contain the appropriate blocks to accomplish a desired task, users may define custom libraries by either modifying an existing block's code or creating a new one from scratch. *Extend* uses the ModL programming language which is very similar to C. Figure 1 shows a sample screen shot of the *Extend* desktop.

2. Random Numbers

Extend uses the "Minimal Standard" as its default random number generator. First proposed by Lewis, Goldman, and Miller in 1969, the minimal standard random number generator is a well-tested simple multiplicative congruential algorithm.

Extend uses a master random number seed at the beginning of each simulation run that the modeler can either specify or let *Extend* randomize. *Extend* also provides the option of continuing the same random number streams over replications.

Extend assigns a unique identifying number to each block in a model. If a block's function is to supply a random input for some process, then the *Extend*-assigned number offsets the master random number seed for that block. As a result, each block generates its own independent stream of random numbers.

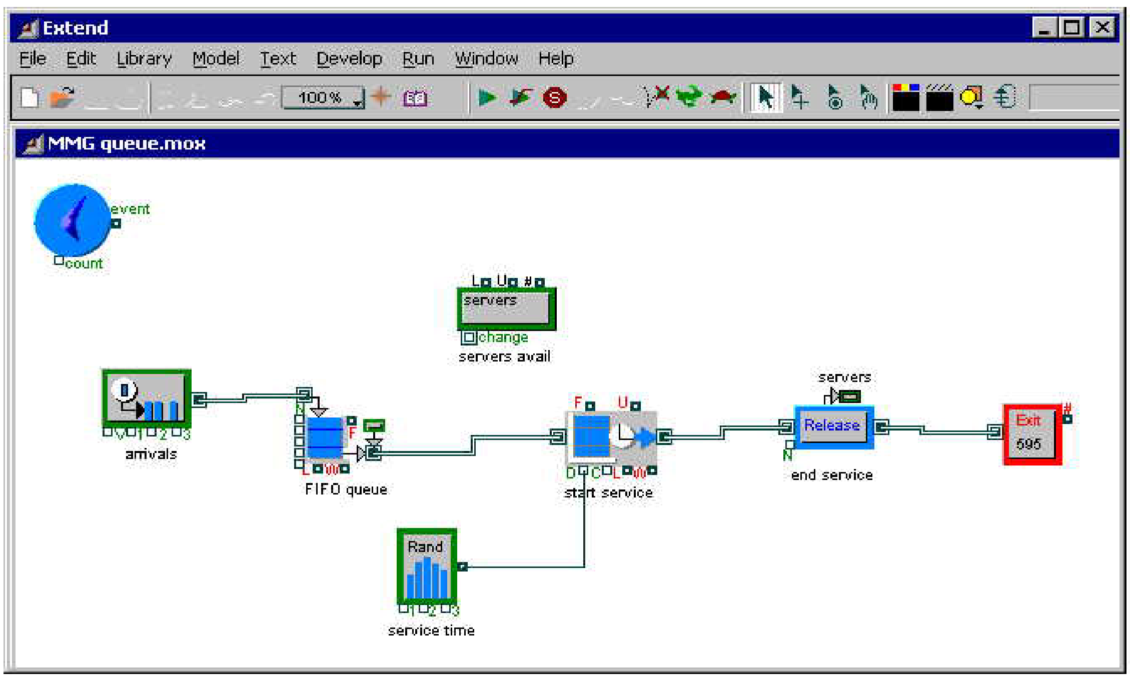

FIGURE 2. *EXTEND* DESKTOP. BLOCKS ARE DRAGGED ONTO THE DESKTOP AND CONNECTED TO PRODUCE A MODEL.

B. DEVELOPMENT OF MODELS

Because of the size and complexity of the NAVAIR TCS *Extend* model, it is difficult to modify it to incorporate the changes necessary to represent the alternative CONOPS and TEL arrival processes addressed in this thesis. Run time is also an issue for the NAVAIR model. A single run, consisting of 50 replications, takes about 90 minutes. For these reasons, flexible models with less detail and shorter run-times than that of NAVAIR are implemented in *Extend* and exercised.

C. PARAMETERS

1. Parameters Obtained from NAVAIR

The models implemented for this thesis use many of the same processing distributions and parameters, as does the NAVAIR model. Table 1 summarizes the unclassified distributions and parameters obtained from NAVAIR. They are implemented in all models developed for this thesis.

Task	Distribution	Parameters			
		Mean (seconds)	Standard Deviation (seconds)	Minimum (seconds)	Maximum (seconds)
GMTI revisit rate	constant	120	0	120	120
Form SAR spot image	constant	17	0	17	17
Search SAR image	lognormal	30	10	0	Infinity
ID target	lognormal	15	1.5	0	Infinity
Decision	lognormal	30	3	0	Infinity
DPPDB pre-registration	lognormal	21.1	56.7	11	93
DPPDB post-registration	constant	14.5	0	14.5	14.5

TABLE 1. DISTRIBUTIONS AND PARAMETERS OBTAINED FROM NAVAIR. THESE ARE COMMON TO ALL MODELS DEVELOPED.

2. TEL Dwell Times

TEL dwell times play an integral role in this analysis, but specific characteristics of TELs are classified. Therefore, surrogate mean dwell times are derived from TCS timeline goals. The TCS threshold and visionary timeline goals, from TCT detection to weapon impact, are 30-minutes and 10-minutes, respectively (reference 5).

Short, medium, and long-dwell TELs representing different technology threats are assumed for the models. The mean loss times for medium and long-dwell TELs are 20 minutes and 30 minutes, respectively. Mean loss times for short-dwell TELs are assumed to be 10 minutes. These last TELs intend to represent a high-technology threat that is difficult for the TCS system to engage.

Each TEL type’s dwell time distribution is assumed to be lognormal. In this thesis, the lognormal distribution is always parameterized in terms of the mean and standard deviation of the dwell time, where the dwell time is log-normally distributed.

D. VARIANCE REDUCTION: COMMON RANDOM NUMBERS

The goal of the simulation is to quantify MOEs to support the evaluation of alternative TCS operating procedures and system designs against the baseline CONOPS developed by NAVAIR. Therefore, it is desirable to use a variance reduction technique that will aid the comparison of alternatives (reference 7).

Using common random numbers is a variance reduction technique that induces positive correlation on the simulation output measures of effectiveness (MOE) (reference 7). In this thesis, one replication for different CONOPS will share the same arrival process of TELs and the same TEL dwell times. The induced correlation will decrease the variability of the simulation statistics and decrease the number of replications needed to assess statistically significant differences in the measures of performance.

E. IMPLEMENTATION OF THE TCS ARCHITECTURE AND CONOPS

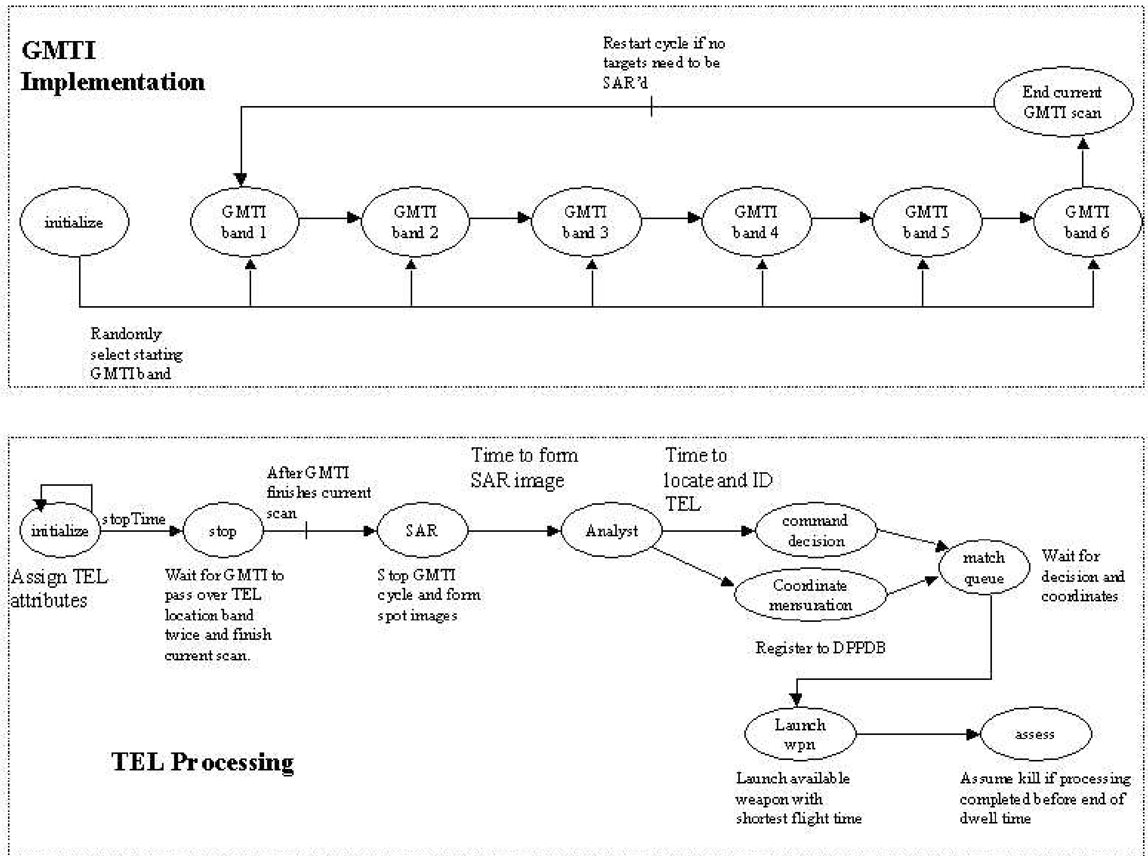

FIGURE 3. EVENT GRAPH FOR THE BASELINE TCS ARCHITECTURE.

1. GMTI Implementation

The GMTI radar's behavior shown in Figure 3 is modeled as a discrete event process. The sensor's field of view (FOV) is modeled using six bands that represent the location of the GMTI radar beam at any given time during a simulation. Band 1 represents the area closest to the sensor and band 6 represents the maximum range. The sensor model used in this research assumes a two-minute revisit rate. The model also assumes that the GMTI radar beam takes the same amount of time to scan each band. As a result, the radar spends twenty seconds in each band. It then revisits the same band every two minutes, unless SAR imagery is formed at the end of a completed cycle.

During the initialization of each run or replication, a starting location band is randomly chosen according to an discrete uniform distribution on the set {1,2,3,4,5,6}. This is because the beam is equally likely to be in any of the six bands at any given time. From here, the radar sequentially scans each band until completing band 6. The sensor then increments a counter and returns to band 1, if no targets are present in the SAR queue. This constitutes a completed scan. The cycle is then repeated continuously throughout the simulation run. The purpose of the counter is to store the number of completed cycles in order to determine the time at which the GMTI loses track of a stopped TEL. This concept is explained further in the next sub-section.

2. SAR Implementation

The model generates the number of TEL objects specified by the user at the beginning of each simulation. Upon entering the model, TELs are immediately assigned attributes that are carried with them throughout the simulation. These attributes determine the locations and times at which the TELs will stop to conduct launch operations. The locations at which the TELs stop correspond to the GMTI sensor bands. Each TEL is randomly assigned to one of these bands, independently, using a discrete uniform distribution on the set {1,2,3,4,5,6}.

The TELs wait in a holding queue while the GMTI process continues to cycle, and the simulation clock advances in the background. Individual TELs are then released from the holding queue when the simulation time reaches their stop time. The model then compares the TEL's location band to the current GMTI band in order to determine when it will be able to form a SAR image. First, recall that a TEL must be lost for two consecutive GMTI scans before it is eligible for spot imaging. If the TEL's stop location band is before the current sensor band, the GMTI has already passed the target. The sensor must then finish its current scan and complete two additional scans before placement of the TEL in the SAR queue. Recall that a TEL must be stationary for two consecutive GMTI scans before it is eligible for SAR imagery. If the TEL location band is after the current GMTI band, the sensor has not passed the target on the current scan. Therefore, the GMTI needs to finish its current scan and complete one additional scan before the TEL is placed in the SAR queue.

In some cases, the stopped TEL and the GMTI radar beam may be in the same location band. Because actual movement and locations are not modeled, a uniform random number is drawn in order to determine if the GMTI loses track on the current or subsequent scan. Each outcome is assumed equally likely, so if the uniform random variable is less than 0.5, the TEL is lost (stopped moving) on the current scan; otherwise, the TEL is lost on the subsequent scan. Figure 4 illustrates an example of the time it may take to lose a GMTI track on a single TEL.

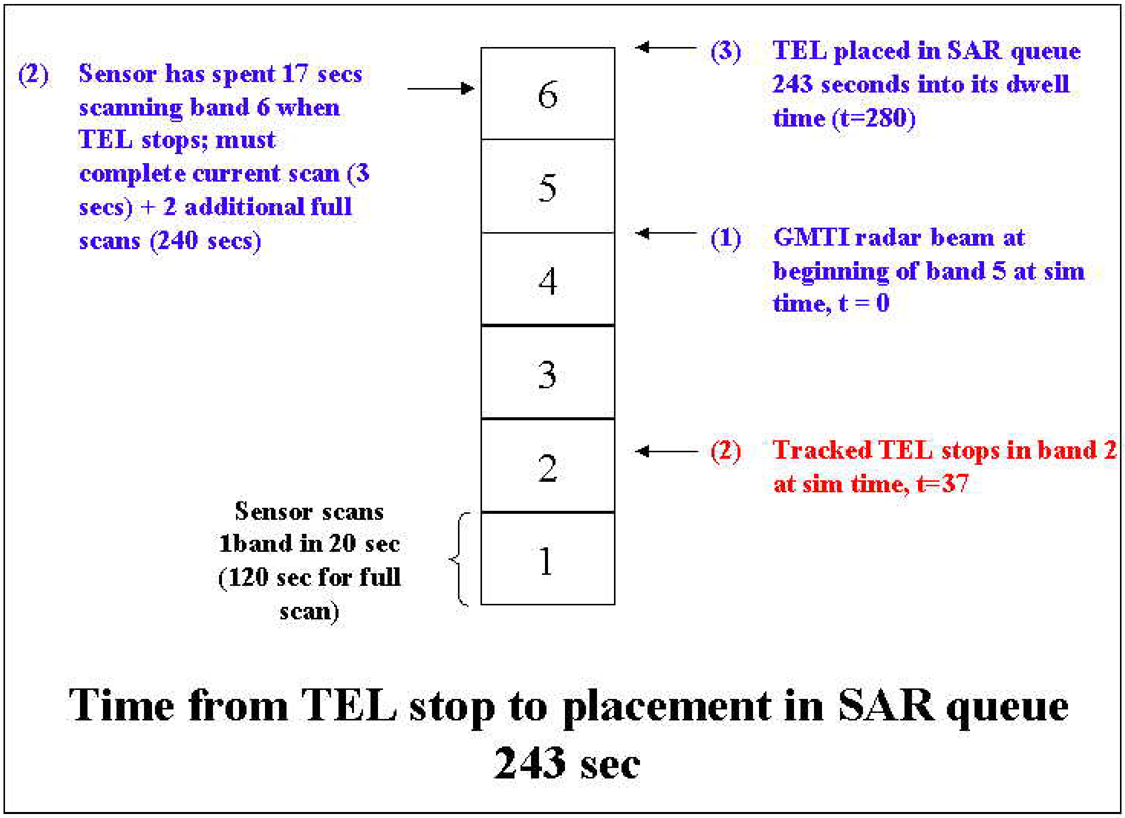

FIGURE 4. TIME TO DETECT A STOPPED TEL. THE BLOCKS LABELED ONE THROUGH SIX REPRESENT THE GMTI SENSOR BANDS. IN THIS CASE, THE TEL STOPS AFTER THE SENSOR HAS PASSED OVER ITS LOCATION DURING THE CURRENT GMTI SCAN.

At the end of each completed GMTI scan cycle, the simulation sends all detected stopped TELs to the SAR queue and stops the GMTI process before it begins a new cycle. If no SAR imagery is required at the end of a completed scan, the GMTI starts the next cycle without interruption. Depending on the number of confirmed lost tracks during the completed scan, there may be multiple image requests. The simulation then removes TELs individually from the SAR queue on a FCFS basis. The simulation holds each TEL removed from the SAR queue for a 17 second constant delay. This delay represents the time required to form an individual spot image, before sending it to the command center for analysis. Only one SAR image can be formed at a time. The simulation reactivates the GMTI process once spot images have been formed for all TELs in the SAR queue (see Figure 3).

3. Weapon Flight Times

Table 2 summarizes the number of weapons and the proximity to the TBM launch area for each shooter location. All targets within the TBM launch area are assumed to be at the same range from a given shooter platform.

Launch Platform	Number of Platforms	Total Weapons Available	Range to Target (nmi)	Time of Flight (minutes)
UCAV	1	2	50	1.32
F/A-18	4	16	200	5.27
Surface ships	1	100	500	13.19

TABLE 2. AVAILABLE WEAPONS, RANGE, AND TIME OF FLIGHT TO TARGETS

The simulation always chooses the available weapon with the shortest time of flight to engage a target. Flight times are calculated by dividing a shooter platform's fixed range to the target area by the weapon's average speed.

4. TEL Arrival processes

a. Coordinated Launch

The coordinated TBM launch models assume that all TELs fire a single TBM within a five-minute interval. Given the number of arrivals, the conditional distribution of the unordered TBM launch times is uniform on the interval in which they arrive. This thesis assumes that TEL stops or TBM launches occur on the interval [0,300] seconds.

Dwell times for each TEL are then determined by an independent random draw from its respective dwell time distribution. Since launches are assumed to occur halfway through each TEL's dwell time, the TEL stop times are calculated by subtracting half the dwell time from the launch time.

b. Coordinated Stop

The coordinated TEL stop models assume that all TELs stop at their launch locations within a five-minute window. Since the number of TELs in the attack is known in the simulation (not in the real world), the conditional distribution of the unordered TEL stop times is uniform on the interval [0,300] seconds. Loss times are determined by adding the random draw from the appropriate dwell time distribution to the stop time. TEL launch times are determined by adding half their dwell time to their stop time.

5. Track-While-Scan

The same approach described in the SAR Implementation section is used to model the track-while-scan capability until information regarding a stopped TEL enters the holding queue.

Once a stopped TEL's information enters the holding queue, the simulation compares the TEL location band to the current GMTI band. The stopped TEL's information is held in this queue until the GMTI completes the first scan during which it actually passes over the TEL’s location band. The information is then sent to a second queue where it is held until the GMTI reaches the TEL’s location band on a second consecutive pass. The TEL’s information is then immediately sent to the SAR queue for spot imaging without any interruption of the GMTI process.

6. Updating

Updating is achieved by sending a copy of a generated TEL’s information to a parallel process after it has been determined to have stopped. The information is held in a queue until the current simulation time exceeds the TEL’s leave time (the TEL’s dwell time is over and it starts to move). The information is then sent to a second queue where it is held until the GMTI sensor arrives at the area in which the TEL is moving (the TEL is assumed to be in its original location band). This process represents the GMTI reacquiring the lost track. Once this moving target is detected, its information enters the FCFS SAR queue with all other TEL information that is waiting for SAR imaging. No confirming scan is necessary. The imagery of the suspected stop location of the now moving target is then analyzed separately from new targets. If the TEL is no longer at the stop location, it will be aborted in the mensuration and shooter selection processes. If the initial TEL has not passed through both of these points at the time it is determined to have left the stop location, it exits the system without being engaged. Processing continues otherwise.

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IV. ANALYSIS

A. ORGANIZATION AND METHODOLOGY

This chapter documents and examines simulation results obtained from the models described in Chapter III. Table 3 highlights the major differences among these models. It begins with a description of the simulation output MOEs and the statistical test used for analysis. This description is followed by verification results between the baseline model developed for this thesis and NAVAIR TCS *Extend* model. Sections E and F compare the effectiveness of the alternative CONOPS and track-while-scan capability against the coordinated TBM launch, and the coordinated TEL stop baseline arrival processes, respectively. These sections are followed by discussions of the sensitivity of the simulation results to lognormal dwell time standard deviation, the TEL arrival processes, and the shooter selection policy. This chapter ends with a discussion of the impact of TCS system congestion.

Results of the simulation runs for the models displayed in Table 3 are divided into two cases for analysis; coordinated TBM launches and coordinated TEL stops. Except for the priority queue simulations, each case consists of 18 simulation runs. A simulation run consists of a unique set of input parameters and CONOPS. Each run has a different specified number of same-type TEL arrivals in a five-minute window and two lognormal dwell time distributions for each TEL type as inputs. The lognormal dwell time distributions for a given TEL type differ only in standard deviation. The means are equal. All simulation runs are replicated 50 times. A *replication* is defined here as a single realization of the simulation model for a given set of input parameters and CONOPS.

CONOPs/Technology Enhancements	GMTI and SAR	Queuing Disciplines	Updating
Baseline	GMTI and SAR radars cannot operate simultaneously. GMTI is the default mode. While targets are in the SAR queue or spot images are being formed, the GMTI cannot update or acquire tracks.	All queues are FCFS	No updates are made. All TELs are completely processed once entering the TCS system, even if they leave. This includes launching a weapon at a TEL that has completed its dwell time.
Simultaneous GMTI and SAR	GMTI and SAR radars operate simultaneously. The GMTI can continue to update current and acquire new tracks while SAR images are formed.	All queues are FCFS	No updates are made. All TELs are completely processed once entering the TCS system, even if they leave. This includes launching a weapon at a TEL that has completed its dwell time.
LIFO queue discipline	GMTI and SAR radars cannot operate simultaneously. GMTI is the default mode. While targets are in the SAR queue or spot images are being formed, the GMTI cannot update or acquire tracks.	The analyst queue is LIFO. All other queues remain FCFS.	No updates are made. All TELs are completely processed once entering the TCS system, even if they leave. This includes launching a weapon at a TEL that has completed its dwell time.
Priority queues	GMTI and SAR radars cannot operate simultaneously. GMTI is the default mode. While targets are in the SAR queue or spot images are being formed, the GMTI cannot update or acquire tracks.	All queues prioritize TELs based on their mean dwell times. TELs with the same mean dwell time are treated as FCFS.	No updates are made. All TELs are completely processed once entering the TCS system, even if they leave. This includes launching a weapon at a TEL that has completed its dwell time.
Updating	GMTI and SAR radars cannot operate simultaneously. GMTI is the default mode. While targets are in the SAR queue or spot images are being formed, the GMTI cannot update or acquire tracks.	All queues are FCFS	Once a TEL completes its dwell time, the GMTI can reacquire the track and request another SAR image. If the TEL is still in the system, it is removed from further processing.

TABLE 3. DESCRIPTION OF CONOPS AND TECHNOLOGY ENHANCEMENTS. THIS TABLE HIGHLIGHTS THE MAJOR DIFFERENCES AMONG THE MODELS.

Because prioritizing TELs requires at least two TEL types, a new baseline is developed for the coordinated TBM launch and coordinated TEL stop arrival processes.

B. MEASURES OF EFFECTIVENESS (MOE)

This thesis does not address weapon accuracy or lethality; both are assumed perfect. Instead, it is simply concerned with whether or not a TEL is processed and engaged before its dwell time expires. A TEL's *processing time* is the amount of time after the TEL stops until a shooter platform is selected for engagement; it does not include the weapon fly-out time.

The primary MOEs used for the comparison of alternative CONOPS are the mean number of TELs that have been engaged before leaving their launch sites and the mean number of weapons expended for each set of 50 replications. Except for the models that allow updating, the latter MOE is the number of TELs in the launch wave because all TELS have one weapon launched against them.

Another MOE, the average (estimated mean) remaining dwell time is applied to the track-while-scan capability. This MOE excludes weapon flight times. It is calculated by averaging the difference between a TEL’s processing time (excluding weapon time of flight) and its dwell time across replications of a simulation run. The average remaining dwell time of a TEL will be negative if the estimated mean time to process the TEL is greater than the TEL’s estimated mean dwell time. This MOE is useful for determining the average time that is available for weapon fly-out before a TEL is lost.

C. COMPARING MODELS: THE PAIRED-T CONFIDENCE INTERVAL

Because of the positive correlation introduced by common random numbers, we construct *paired-t confidence intervals* for the simulation output MOEs in order to assess the performance of each alternative system against the corresponding baseline system (reference 7). The paired-*t* confidence interval is also used to verify the baseline model results against the NAVAIR TCS *Extend* model.

Replications within a single simulation run are independent. However, the arrival processes and TEL dwell times are the same in each replication for the alternative and baseline models. This implies that the pairs of differences between the MOEs generated by the alternative and baseline models for each replication are independent.

Let X_i and Y_i be the i^{th} simulated MOE for the altered and baseline systems, respectively. There are 50 replications for each system. Define $D_i = X_i - Y_i$ as the difference between the alternative and baseline MOEs for replication i. The D_i's are independent and identically distributed random variables and we wish to construct a 95 percent confidence interval for the expected difference between the MOEs of the alternative and baseline systems. We take the expected value of the alternative MOE to be $E[\boldsymbol{X}]$, estimated by the mean $\bar{X}$, and that of the baseline as $E[\boldsymbol{Y}]$, estimated by the mean $\bar{Y}$; their difference is $\bar{d} = \bar{X} - \bar{Y}$. Let $\bar{d}$ and s_D be the mean and standard error of the D_i's, respectively. The 2.5th percentile of a t-distribution with 49 degrees of freedom is -2.001. This leads to the approximate 95 percent confidence interval for the expected difference given by $\bar{d} \pm 2.001 s_D$. The confidence interval is an approximation because it is not likely that the D_i's are normally distributed, although their average will tend to be, by the Central Limit Theorem (reference 1, 7).

If the 95 percent confidence interval does not contain zero, the expected difference between the alternative and baseline MOEs is significant at the 5 percent level. Furthermore, if the 95 percent confidence interval does not contain zero and $\bar{d} - 2.001 s_D > 0$ then the alternative system performance is statistically better, in terms of the selected MOE, than the baseline system. The opposite is true if $\overline{d} + 2.001 s_D < 0$. If the 95 percent confidence interval contains zero, then there is no difference between the expected alternative and expected baseline MOEs at the 5 percent level of significance.

D. VERIFICATION OF THE BASELINE MODEL

1. Approach

Simulation results for the baseline model are compared against those of the NAVAIR TCS *Extend* model to ensure correct implementation of the design and CONOPS. The TCS *Extend* model, however, requires a pre-defined launch schedule. Therefore, results were first obtained from the baseline model developed for this thesis. TEL stop, launch, and depart times from each replication were then sent to NAVAIR as input for its model.

The MOE used for verification is the expected value of the number of TELs engaged before dwell time completion. This can also be interpreted as the expected value of the number of kills since the p_k is set to 1. Table 4 summarizes the input parameters used for verification.

	distribution	mean or constant	stdev (sec)	loc (sec)
Simulation				
replications	-	50	-	-
TELS				
number	-	30	-	-
dwell time	lognormal	1200 sec	1200	0
ISR				
GMTI cycle	constant	120 sec	-	-
form spot image	constant	17 sec	-	-
Analyst				
search image	lognormal	30 sec	10	0
ID TEL	lognormal	15 sec	1.5	0
Command Decision				
decide	lognormal	30 sec	3	0
Mensuration				
failure probability	-	0	-	-
pre-register to DPPDB	lognormal	21.1 sec	56.7	11
post-register to DPPDB	constant	14.5 sec	-	-
Weapons				
average speed	constant	Mach 4 (0.632 nmi/sec)	-	-
range	constant	600 nmi	-	-
probability of kill	constant	1	-	-
UCAV				
total weapons	-	2	-	-
flight distance	-	50 nmi	-	-
CAP				
total weapons	-	16	-	-
flight distance	-	200 nmi	-	-
Surface				
total weapons	-	100	-	-
flight distance	-	500 nmi	-	-

TABLE 4. SIMULATION PARAMETERS USED FOR VERIFICATION.

2. Verification Results

For the data obtained from the two models, $\bar{d}$ = -0.200 and s_D = 0.128, leading to the 95 percent confidence interval for the difference in the expected value of the number of TELs killed between the NAVAIR model and the baseline coordinated TBM launch model developed for this thesis. Because the confidence interval contains zero, with 95 percent confidence, there is no statistical evidence of a difference in the expected values of the number of TELs killed in the two models.

E. COORDINATED TBM LAUNCHES

1. Results for the Baseline Architecture and CONOPS

This sub-section reports the results of the baseline TCS architecture and CONOPS developed by NAVAIR for a coordinated TBM launch. These results are used to evaluate the effectiveness of the alternative operating procedures and track-while-scan capability in this section.

Table 5 summarizes the simulation results and TEL input parameters for the coordinated TBM launch times implemented in the baseline model. Each case consists of one TEL type.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE
short	(10,2)	15	**2.7**	**0.13**
		30	**2.7**	**0.12**
		45	**2.8**	**0.13**
	(10,10)	15	**4.3**	**0.23**
		30	**7.1**	**0.29**
		45	**9.1**	**0.30**
medium	(20,5)	15	**12.7**	**0.20**
		30	**15.2**	**0.21**
		45	**16.1**	**0.20**
	(20,20)	15	**8.1**	**0.24**
		30	**13.8**	**0.28**
		45	**17.3**	**0.20**
long	(30,5)	15	**15.0**	**0.00**
		30	**19.7**	**0.21**
		45	**20.9**	**0.26**
	(30,20)	15	**13.2**	**0.21**
		30	**18.9**	**0.19**
		45	**22.6**	**0.37**

TABLE 5. BASELINE RESULTS FOR COORDINATED TBM LAUNCHES. EACH MEAN AND STANDARD ERROR IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMN AS INPUTS. FOR EXAMPLE, THE MEAN AND STANDARD ERROR REPORTED IN THE FIRST ROW ARE FOR 15 TELS THAT SHARE THE SAME LOGNORMAL DWELL TIME DISTRIBUTION MEAN AND STANDARD DEVIATION PARAMETERS.

The baseline performs better as TEL mean dwell times increase. This result is intuitive because the system tends to have more time to engage the TELs before they are lost. However, the average number of successful TEL engagements does not dramatically increase for a given dwell time distribution as the number of TELs in the launch wave increases. These marginal improvements result from system congestion and weapon flight times shown in Figure 5.

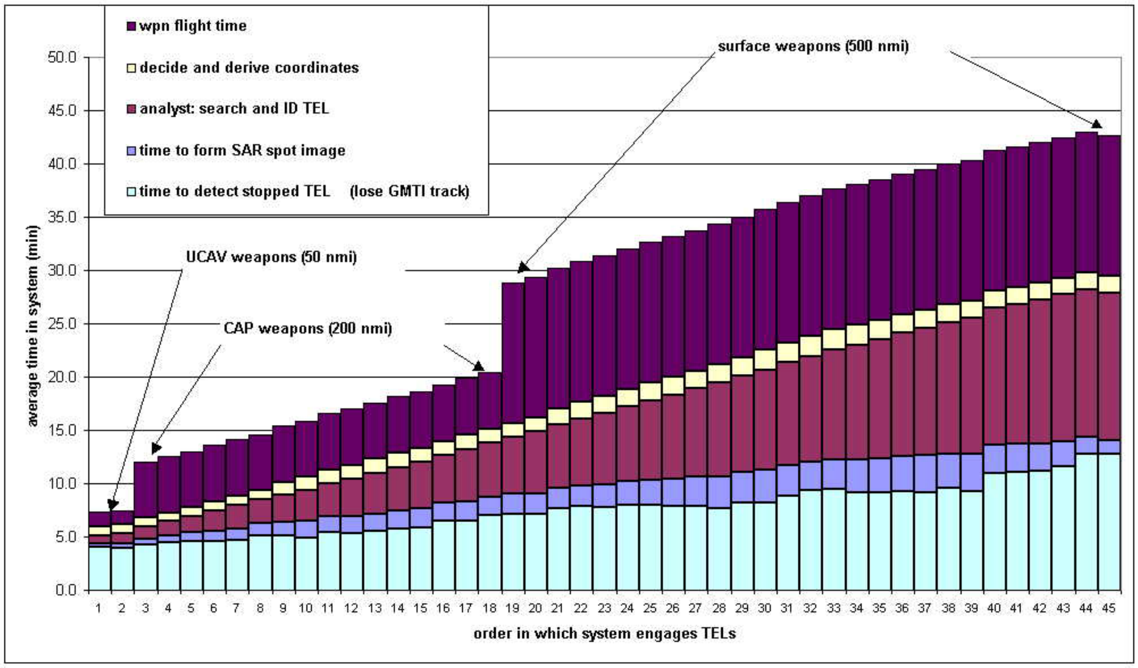

FIGURE 5. BASELINE MODEL MEAN PROCESSING AND WEAPON FLY-OUT TIMES FOR COORDINATED TBM LAUNCHES. THE ESTIMATES ARE BASED ON 30 SIMULATION REPLICATIONS OF 45 MEDIUM-DWELL TELS, EACH HAVING A LOGNORMAL(20,5) DWELL TIME DISTRIBUTION. THE COLUMN NUMBERING ALONG THE X-AXIS REFERS TO THE ORDER IN WHICH THE SYSTEM ENGAGES THE 45 TELS AFTER PROCESSING. THE TOTAL HEIGHT OF EACH COLUMN IS THE SUM OF A TEL'S MEAN PROCESSING TIME AND MEAN WEAPON FLY-OUT TIME. EACH COLUMN IS DIVIDED INTO FIVE STACKS THAT REPRESENT THE AVERAGE TIME IT TAKES THE SYSTEM TO PROCESS THE TEL IN EACH PHASE OF THE KILL CHAIN. THE FIRST 17 TELS THAT ARE ENGAGED HAVE MEAN TIMES TO COMPLETE THE KILL CHAIN LESS THAN THE 20 MINUTE MEAN DWELL TIME; THE REMAINING TELS THAT ARE ENGAGED HAVE MEAN TIMES TO COMPLETE THE KILL CHAIN WHICH ARE LARGER THAN THE MEAN DWELL TIME.

Each column of the stacked bar chart in Figure 5 corresponds to the order in which the 45 TELs in the launch wave are engaged by the baseline system. The total height of each column is the average latency between the time the TEL stops and the time a weapon arrives at the TEL’s location.

Figure 5 divides each column into five stacks. The first four, starting from the bottom, represent the average time the TEL spends waiting in queue and being serviced in that phase of the kill chain. The top, or fifth, stack of each column is the constant weapon flight time to reach the TEL. Flight times are constant because the shooter locations are fixed and are always selected in the same order. These stacks increase as the system engages more TELs because of the availability of weapons. Recall that there are 2 UCAV, 16 CAP and 100 surface weapons with fly-out distances of 50, 200, and 500 nautical miles to the TAI, respectively. Also, recall that the weapon having the shortest time of flight to the target is always selected to engage a TEL. Therefore, the UCAV shooter always engages the first two TELs and the four F/A-18 CAP shooters always engage the next 16. The surface shooter engages the remaining TELs from a range of 500 nmi. The progression of these distances translates to longer flight times.

The stacked bar chart in Figure 5 indicates that congestion and long weapon flight times tend to limit the effectiveness of the baseline system against a high volume of medium-dwell TELs conducting coordinated TBM launches. The mean time required to physically put a weapon on target begins to exceed the 20-minute mean dwell time after the seventeenth TEL is engaged by the system. This agrees with the results for the same inputs in Table 5.

The goal of the alternative operating procedures and track-while-scan capability is to shorten the total height of each column and/or rearrange the bottom four stacks so that average total times required to process and engage the TELs usually fall below TEL mean dwell times.

2. Track-while-scan Results

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	4.0	0.22	[0.92, 1.60]
		30	4.1	0.19	[1.09, 1.71]
		45	4.1	0.19	[0.97, 1.55]
	(10,10)	15	5.2	0.30	[0.66, 1.18]
		30	8.5	0.32	[1.12, 1.72]
		45	11.1	0.28	[1.61, 2.35]
medium	(20,5)	15	14.2	0.14	[1.21, 1.79]
		30	16.7	0.18	[1.17, 1.87]
		45	17.3	0.12	[0.92, 1.64]
	(20,20)	15	9.2	0.22	[0.79, 1.37]
		30	15.3	0.24	[1.09, 1.75]
		45	18.1	0.20	[0.46, 0.98]
long	(30,5)	15	15.0	0.00	[0.00, 0.00]
		30	21.7	0.30	[1.58, 2.42]
		45	23.1	0.28	[1.71, 2.65]
	(30,20)	15	14.2	0.16	[0.65, 1.23]
		30	19.8	0.25	[0.66, 1.18]
		45	25.1	0.42	[2.01, 2.87]

TABLE 6. TRACK-WHILE-SCAN RESULTS FOR COORDINATED TBM LAUNCHES. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE TRACK-WHILE-SCAN AND BASELINE MOES. ALL BUT ONE OF THESE CONFIDENCE INTERVALS SUGGEST THAT THE TRACK-WHILE-SCAN SYSTEM PERFORMS STATISTICALLY BETTER THAN THE BASELINE SYSTEM IN TERMS OF MEAN NUMBER OF TELS KILLED. THERE IS NO IMPROVEMENT OR DEGRADATION FOR THE CASE CONSISTING OF 15 LONG-DWELL TELS WITH THE LOGNORMAL (30,5) DWELL TIME DISTRIBUTION BECAUSE BOTH THE BASELINE AND TRACK-WHILE-SCAN SYSTEMS WERE ABLE TO KILL EVERY TEL IN THE LAUNCH WAVE IN EVERY REPLICATION.

All but one of the 95 percent confidence intervals in Table 6 indicate that implementing a sensor with track-while-scan capability results in more successful TEL engagements. The confidence interval for the 15 long-dwell TELs with the lognormal (30,5) parameters has an upper and lower bound equal to zero because both the baseline and track-while-scan models are able to successfully engage all TELs in all replications.

Although the track-while-scan results are statistically better than the baseline, the practical improvement on the mean number of TELs killed for each set of inputs is marginal. These small differences are a result of system congestion and the fly-out time of the available weapons used in the simulations.

Figure 6 illustrates the change in mean remaining TEL dwell times when the track-while-scan sensor capability is added to the baseline system. Implementation of the new capability results in marginal improvements in the mean times at which shooter platforms may engage the TELs. Furthermore, the magnitude of these changes has little impact on the effectiveness of the surface shooter platform under the current shooter selection policy. In fact, some of the actual mean remaining dwell times that correspond to the relative changes depicted in Figure 6 may actually be negative. That is, there is a tendency for some TELS in the latter stages of an attack wave to be lost before a shooter platform is able to engage them (see Figure 9).

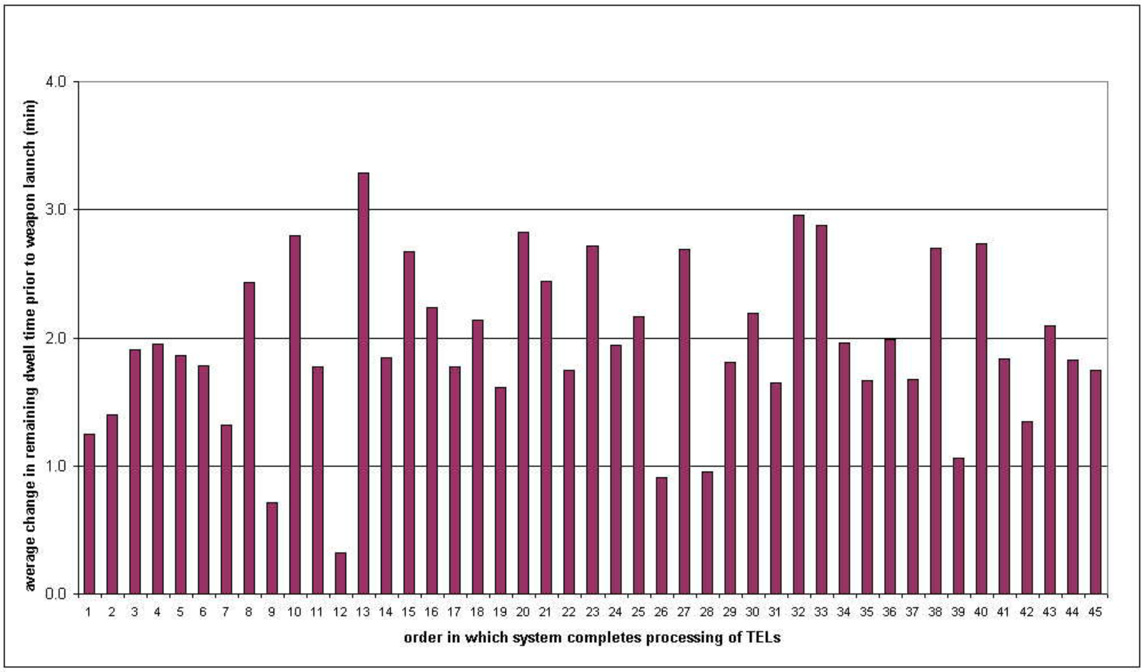

FIGURE 6. CHANGE IN AVERAGE REMAINING DWELL TIMES BETWEEN THE TRACK-WHILE-SCAN AND BASELINE MODELS. THE ORDERING OF THE COLUMNS CORRESPONDS TO THE ENGAGEMENT ORDER OF THE 45 LOGNORMAL (20,5) MEDIUM-DWELL TELS. THE HEIGHT OF EACH COLUMN IS THE AVERAGE DIFFERENCE BETWEEN THE BASELINE AND TRACK-WHILE-SCAN REMAINING DWELL TIMES ACROSS 30 SIMULATION REPLICATIONS FOR THE COORDINATED LAUNCH CASE. FOR EXAMPLE, A WEAPON HAS, ON AVERAGE, THREE ADDITIONAL MINUTES OF FLIGHT TIME AVAILABLE IN THE TRACK-WHILE-SCAN MODEL TO REACH THE LOCATION OF THE 13TH ENGAGED TEL BEFORE ITS DWELL TIME EXPIRES.

The results in Figure 6 only show the net change in the mean weapon fly-out time available before a TEL is lost. Figure 7 illustrates that the track-while-scan capability reduces the average time latency to detect stopped TELs; however, increased image processing times due to congestion negate most of these time savings.

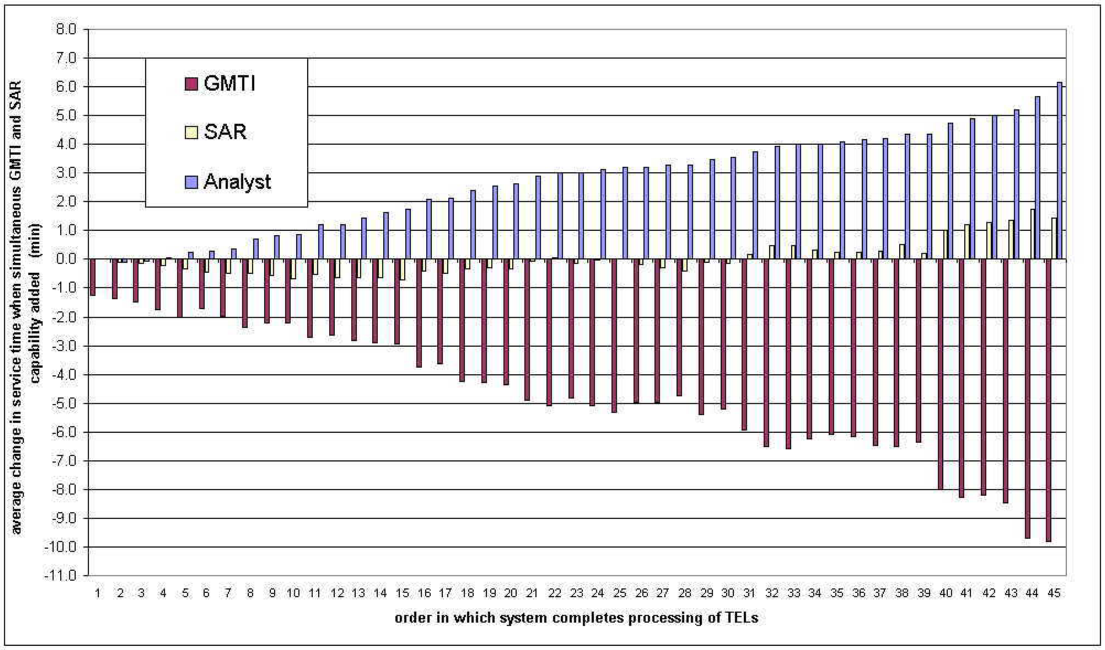

FIGURE 7. CHANGE IN AVERAGE TEL PROCESSING TIMES BETWEEN THE TRACK-WHILE-SCAN AND BASELINE MODELS FOR COORDINATED TBM LAUNCHES. THIS CHART SHOULD BE READ AS 45 SETS OF THREE COLUMNS EACH. THE ARRANGEMENT OF THE SETS ALONG THE X-AXIS CORRESPONDS TO THE ORDER IN WHICH 45 LOGNORMAL (20,5) MEDIUM-DWELL TELS ARE ENGAGED BY THE TCS MODELS. THE FIRST, SECOND, AND THIRD COLUMNS IN EACH SET ARE THE AVERAGE CHANGES IN SERVICE TIMES, BASED ON 30 REPLICATIONS, FOR THE GMTI, SAR, AND IMAGE ANALYSIS PHASES OF THE KILL CHAIN, RESPECTIVELY (A DECISION AND MENSURATION COLUMN IS OMITTED BECAUSE THE CHANGE IN SERVICE TIMES ARE NOT STATISTICALLY SIGNIFICANT). COLUMN HEIGHTS ARE NEGATIVE IF THE TRACK-WHILE-SCAN AVERAGE SERVICE TIMES ARE LESS THAN THE BASELINE. FOR EXAMPLE, THE 45TH TEL PROCESSED BY BOTH SYSTEMS SPENDS ON AVERAGE 10 MINUTES LESS IN THE GMTI PHASE, 1 MINUTE MORE IN THE SAR PHASE, AND 6 MINUTES MORE IN THE ANALYST PHASE FOR THE TRACK-WHILE-SCAN MODEL WHEN COMPARED TO THE BASELINE.

Figure 7 illustrates the ability of the track-while-scan capability to detect TEL stops sooner, on average, than the baseline model. However, the increased rate at which stopped TELs are confirmed induces congestion in the image analysis phase of the kill chain. This negates most of the time savings provided by the track-while-scan capability. These results imply that multiple enhancements, e.g. more image analysts and DPPDB workstations, are needed to improve upon baseline performance.

3. LIFO Analyst Queue

Implementation of the LIFO queue discipline does not improve upon the baseline model results. In fact, it performs statistically worse for some of the medium and long-dwell TEL cases. LIFO results are reported in Appendix A.

The simulation representation of coordinated TBM launches influences the effectiveness of the LIFO queue discipline. Recall that the coordinated TBM launch case assumes that all TELs launch a single TBM within a five-minute window. In order to obtain each TEL's stop time, half of its randomly drawn dwell time is subtracted from its scheduled launch time. Since all TBM launches occur during a short time interval, the TELs having the longest dwell times tend to stop first. Because these TELs have loss times that are usually drawn from the right tail of a positively skewed lognormal distribution, there may be significant gaps between the stop times for the first few TELs. The system is usually able to process these TELs without any delays in queues. As time approaches the five-minute launch window, the TELs that stop tend to have shorter dwell times and queues begin to form in the system. At this point, the LIFO queue discipline forces the system to process TELs that usually have shorter dwell times than the ones preceding them. As a result, the LIFO queueing discipline forces the TCS system to service TELs that are less likely to be successfully engaged. Figure 8 illustrates these points.

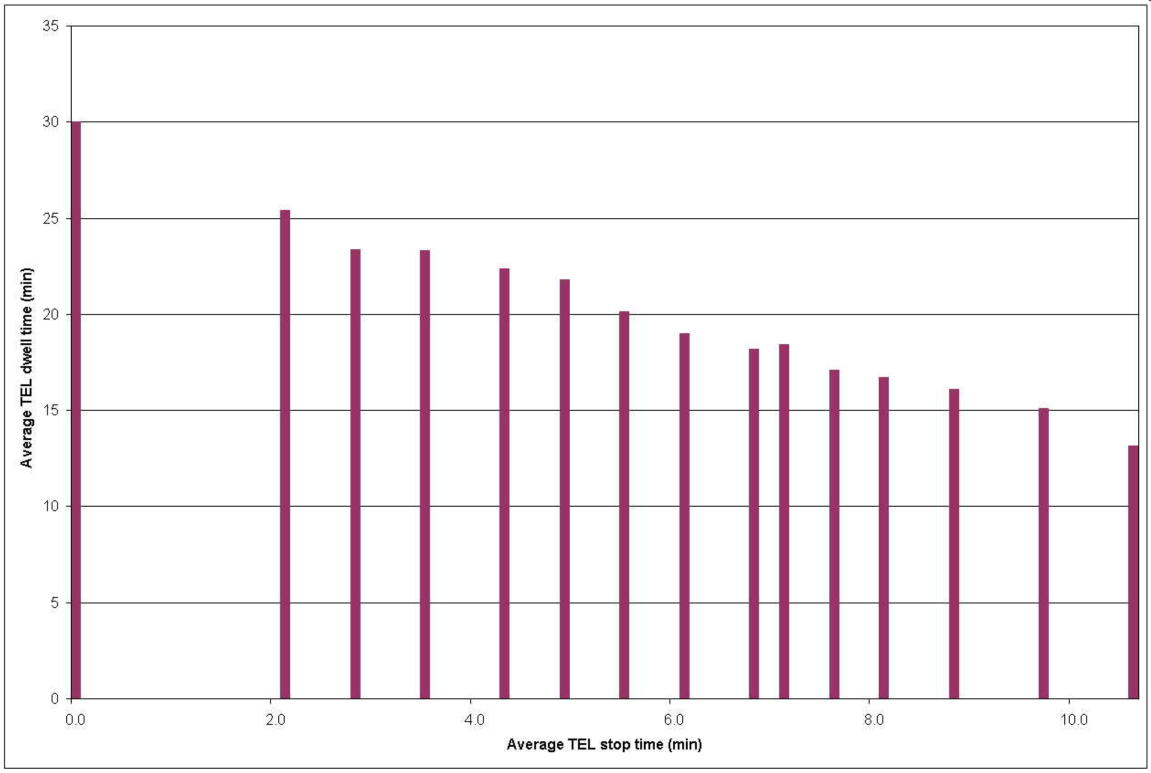

FIGURE 8. MEAN TEL STOP AND DWELL TIMES FOR 30 REPLICATIONS OF A COORDINATED TBM LAUNCH WAVE CONSISTING OF 15 LOGNORMAL (20,5) MEDIUM-DWELL TELS. STOP TIMES ARE RELATIVE TO THE STOP TIME OF THE FIRST TEL IN THE LAUNCH WAVE. FOR EXAMPLE, THE FIRST TEL IN A SIMULATED LAUNCH WAVE ALWAYS STOPS AT TIME 0, THE SECOND TEL STOPS SOME AMOUNT OF TIME AFTER THE FIRST, AND SO ON. STOP TIMES FOR A GIVEN REPLICATION ARE CALCULATED BY SUBTRACTING THE TIME OF THE FIRST STOP IN THE LAUNCH WAVE FROM EACH TEL'S STOP TIME. THE MEAN STOP TIME FOR EACH OF THE 15 TELS IS THE AVERAGE ACROSS THE 30 REPLICATIONS. THE MEAN DWELL TIMES CORRESPOND TO THE STOP ORDER OF THE TELS AND ARE AVERAGED ACROSS THE SAME 30 REPLICATIONS. AVERAGE DWELL TIMES TEND TO DECREASE AS SUCCESSIVE TELS STOP. IN ADDITION, THE AVERAGE TIME BETWEEN ARRIVALS FOR THE FIRST FEW TELS IS GREATER THAN THOSE FOR TELS ARRIVING IN THE MIDDLE OF THE LAUNCH WAVE.

4. Updating

Figure 9 illustrates that many TELs may be lost before shooter platforms in the baseline system are able to launch weapons at them. Attempting to engage these TELs wastes missiles and subjects the system to additional congestion. Therefore, the TCS system should have the capability to periodically observe detected TELs and abort further processing if the TELs are lost, as long it does not significantly limit overall effectiveness.

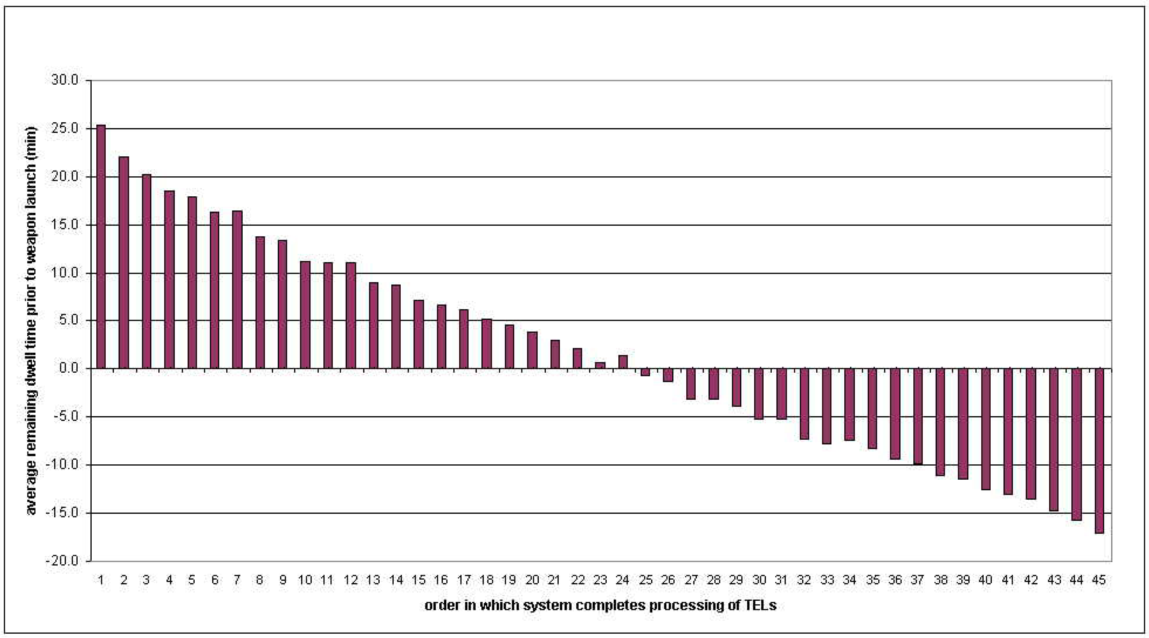

FIGURE 9. BASELINE SYSTEM AVERAGE REMAINING DWELL TIMES BEFORE ENGAGEMENT FOR COORDINATED TBM LAUNCHES. THIS CHART SHOWS THE AVERAGE REMAINING LOSS TIMES, BASED ON 30 REPLICATIONS, FOR A COORDINATED TBM LAUNCH WAVE CONSISTING OF 45 LOGNORMAL (20,5) MEDIUM-DWELL TELS. NOTE THAT ABOUT HALF OF THE TELS, ON AVERAGE, HAVE AVERAGE DWELL TIMES WHICH ARE LESS THE THEIR MEAN TIMES BEFORE A WEAPON IS ASSIGNED TO THEM.

a. Mean Number of TELs Engaged Prior to Dwell Time Completion

Except for one case, the updating CONOPS model produces results that are statistically equivalent to the baseline model in terms of the mean number of TELs killed. The one exception is the case that consists of 15 short-dwell TELs with lognormal (10,2) dwell times. Here, the updating CONOPS model performs slightly worse than the baseline. Complete results for all cases are reported in Appendix A.

This implies that the updating CONOPS will be advantageous if it saves weapons.

b. Mean Number of Weapons Expended

The previous results for the mean number of TELs killed coupled with the mean number of weapons saved results shown in Table 7 suggest that the updating CONOPS has the potential to save many weapons without affecting the mean number of TELs killed. For example, refer to the case consisting of 45 short-dwell TELs with lognormal (10,10) dwell time distributions. The 95 percent confidence interval indicates that the updating CONOPS saves 14 to 16 weapons, on average, when compared to the corresponding baseline case. This is significant considering that, for the same case, there is no statistical evidence that a difference exists in the mean number of TELs killed between the two models.

For a particular TEL type, the updating CONOPS saves more weapons, on average, as the size of the attack wave increases. This is because large attack waves congest the system and tend to increase TEL processing times. As a result, the system is more likely to abort a detected TEL that has completed its dwell time before a shooter platform has been assigned to engage it.

The updating CONOPS on the average saves the most weapons against the attack wave of 45 lognormal (10,10) short-dwell TELs because processing times tend to be much longer than TEL dwell times. However, as TEL dwell times increase, the number of weapons saved diminishes because the dwell times of lost TELs tend to expire during the 13-minute flight time of surface-launched weapons (see Figure 14).

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of weapons expended (MOE)	std error of mean	95% confidence interval for expected number of weapons saved (MOE baseline system - MOE altered system)
short	(10,2)	15	14.5	0.11	[0.28, 0.72]
		30	26.1	0.25	[3.43, 4.45]
		45	37.1	0.35	[7.18, 8.58]
	(10,10)	15	12.1	0.19	[2.47, 3.25]
		30	21.8	0.26	[7.65, 8.71]
		45	30.2	0.33	[14.11, 15.45]
medium	(20,5)	15	15.0	0.00	[0.00, 0.00]
		30	27.5	0.20	[2.11, 2.93]
		45	36.6	0.30	[7.76, 8.96]
	(20,20)	15	14.0	0.13	[0.78, 1.30]
		30	25.9	0.23	[3.67, 4.57]
		45	36.4	0.30	[8.02, 9.22]
long	(30,5)	15	15.0	0.00	[0.00, 0.00]
		30	30.0	0.02	[- 0.02, 0.06]
		45	42.5	0.20	[2.09, 2.91]
	(30,20)	15	15.0	0.02	[- 0.02, 0.06]
		30	28.9	0.17	[0.72, 1.40]
		45	40.2	0.28	[4.24, 5.36]

TABLE 7. UPDATING CONOPS: MEAN NUMBER OF WEAPONS EXPENDED AND MEAN NUMBER OF WEAPONS SAVED FOR COORDINATED TBM LAUNCHES. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL DISTRIBUTION PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE UPDATING AND BASELINE MOES. HOWEVER, BECAUSE THE INTEREST HERE IS THE NUMBER OF WEAPONS SAVED, THE MOE FOR THE UPDATING CONOPS IS SUBTRACTED FROM THE MOE FOR THE BASELINE CONOPS. THE CONFIDENCE INTERVALS INDICATE THAT THE UPDATING CONOPS USUALLY SAVES WEAPONS ON AVERAGE . THE STANDARD ERRORS OF THE MEANS ARE ZERO FOR THOSE CASES IN WHICH A WEAPON WAS EXPENDED AGAINST EVERY TEL IN THE LAUNCH WAVE IN ALL 50 SIMULATION REPLICATIONS. FOR THE CASE CONSISTING OF 45 SHORT-DWELL TELS WITH LOGNORMAL (10,10) DWELL TIME DISTRIBUTIONS, THE UPDATING CONOPS SAVES BETWEEN 14 AND 16 WEAPONS, ON AVERAGE, WHEN COMPARED TO THE CORRESPONDING BASELINE CASE. THIS IS SIGNIFICANT CONSIDERING THAT THERE IS NO STATISTICAL EVIDENCE THAT A DIFFERENCE EXISTS IN THE MEAN NUMBER OF TELS KILLED BETWEEN THE TWO MODELS.

5. Priority Queues

For the priority queue CONOPS, TELs of a particular type are processed before others. It is assumed that a TEL’s type is known perfectly. Priority queues require at least two different TEL types. Because all the models to this point assume same-type TELs for all simulation runs, a new baseline is developed for these two models.

Earlier results have shown that the baseline TCS system cannot consistently engage short-dwell TELs before they are lost. Therefore, the new baseline models do not consider short-dwell TELs.

The simulation generates a random mix of medium and long-dwell TELs, each with probability 0.5. Because of common random numbers, the proportion of medium to long-dwell TELs, the order in which they appear, the times they appear, and their dwell times are preserved for a given set of inputs within each replication for the baseline and priority models. Simulation results for this new baseline are summarized in Table 8.

TEL dwell types	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE
mixed	med: (20,5) long: (30,5)	15	**14.3**	**0.15**
		30	**18.2**	**0.11**
		45	**19.9**	**0.23**
	med: (20,20) long: (30,20)	15	**10.5**	**0.24**
		30	**16.8**	**0.20**
		45	**19.9**	**0.30**

TABLE 8. PRIORITY QUEUE BASELINE RESULTS FOR COORDINATED TBM LAUNCHES. ALL QUEUES ARE FCFS FOR THE BASELINE CASES. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 REPLICATIONS FOR A MIX OF MEDIUM AND LONG-DWELL TELS HAVING THE DISTRIBUTION PARAMETERS IN THE SECOND COLUMN. EACH TEL TYPE IS GENERATED INDEPENDENTLY WITH PROBABILITY 0.5 AND THE TOTAL NUMBER OF GENERATED TELS AGREES WITH THE NUMBER OF TELS IN THE THIRD COLUMN.

a. *Prioritize on Medium-Dwell TELs*

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
mixed	med: (20,5) long: (30,5)	15	**14.5**	**0.09**	**[0.02, 0.38]**
		30	**17.8**	**0.13**	**[- 0.64, - 0.16]**
		45	**18.8**	**0.16**	**[- 1.48, - 0.76]**
	med: (20,20) long: (30,20)	15	**10.6**	**0.25**	[- 0.10, 0.38]
		30	**16.9**	**0.23**	[- 0.11, 0.35]
		45	**19.7**	**0.30**	[- 0.50, 0.10]

TABLE 9. PRIORITIZATION OF MEDIUM-DWELL TELS RESULTS FOR COORDINATED TBM LAUNCHES. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL DISTRIBUTION PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE MEDIUM-DWELL TEL PRIORITIZATION AND PRIORITY QUEUE BASELINE MOES.

For a mix of at least 30 medium and long-dwell TELs having lognormal standard deviations equal to 5 minutes, prioritizing on the medium-dwell TELs results in a smaller mean number of TELs killed than the baseline. Similar to the LIFO CONOPS, this is a result of the simulation representation of the coordinated TBM launch arrival process. Because of the small standard deviations, most of the TEL types initially processed by the system are long-dwell. A few of these, however, may be medium-dwell TELs possessing dwell times drawn from the right tail of the lognormal distribution. Again, recall that TEL launch times are assumed to be at the midpoint of their dwell times. Because of this, most long-dwell TELs are expected to stop about 10 to 15 minutes before the scheduled five-minute launch window. Likewise, most medium-dwell TELs are expected to stop 5 to 10 minutes before the launch window. Any long-dwell TELs waiting in the SAR or analyst queues are pushed to the end once the bulk of the medium-dwell TELs begin to enter the system. Approximately half of the TELs that have arrived at this point are long-dwell. This is significant because the original baseline model results indicate that the system can only successfully engage about 16 medium-dwell TELs with a lognormal standard deviation of 5 minutes. Therefore, it is not surprising that prioritizing on medium-dwell TELs in this case does not improve system performance.

There is no significant difference between the expected value of the MOE for the baseline and the mix of TELs having lognormal standard deviations equal to 20 minutes. The same problem exists as in the 5-minute standard deviation cases; however, it is less evident because the larger dwell time standard deviation spreads the distribution of TEL stops.

b. *Prioritize on Long-Dwell TELs*

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
mixed	med: (20,5) long: (30,5)	15	**14.4**	**0.12**	[0.00, 0.28]
		30	**17.8**	**0.12**	**[- 0.63, - 0.13]**
		45	**18.7**	**0.13**	**[- 1.59, - 0.81]**
	med: (20,20) long: (30,20)	15	**10.8**	**0.25**	**[0.11, 0.45]**
		30	**16.9**	**0.22**	[- 0.13, 0.25]
		45	**19.7**	**0.28**	[- 0.54, 0.06]

TABLE 10. PRIORITIZATION OF LONG-DWELL TELS RESULTS FOR COORDINATED TBM LAUNCHES. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL DISTRIBUTION PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE LONG-DWELL TEL PRIORITIZATION AND PRIORITY QUEUE BASELINE MOES.

For an even mix of at least 30 medium and long-dwell TELs, each type having a lognormal standard deviation equal to 5 minutes, prioritizing on the long-dwell TELs results in fewer successful engagements than the baseline on the average. This can be explained by an argument similar to the medium-dwell TEL prioritization. In this case, medium-dwell TELs that enter the system and have loss times drawn from the right tail of the lognormal distribution must wait until all long-dwell TELs have been serviced. Some of these long-dwell TELs can have loss times that are much smaller than the medium-dwell TELs.

The best queueing discipline for coordinated TBM launches as represented in the simulation is FCFS because most TELs are engaged in descending order of dwell time, regardless of TEL type.

F. COORDINATED TEL STOP TIMES

1. Results for the Baseline Architecture and CONOPS

This sub-section reports the results of the baseline TCS architecture and CONOPS developed by NAVAIR for coordinated TEL stop times. These results are used to evaluate the effectiveness of the alternative CONOPS and the track-while-scan capability in this section.

Table 11 summarizes the simulation results and TEL input parameters for the coordinated TEL stop time cases implemented in the baseline model. Each case consists of one TEL type.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE
short	(10,2)	15	**2.2**	**0.10**
		30	**2.2**	**0.08**
		45	**2.2**	**0.10**
	(10,10)	15	**2.9**	**0.23**
		30	**3.6**	**0.25**
		45	**3.5**	**0.26**
medium	(20,5)	15	**12.4**	**0.22**
		30	**12.7**	**0.26**
		45	**12.4**	**0.27**
	(20,20)	15	**7.7**	**0.29**
		30	**10.5**	**0.32**
		45	**11.6**	**0.35**
long	(30,5)	15	**15.0**	**0.00**
		30	**21.0**	**0.25**
		45	**20.0**	**0.21**
	(30,20)	15	**12.3**	**0.23**
		30	**17.3**	**0.34**
		45	**19.7**	**0.41**

TABLE 11. COORDINATED STOP BASELINE RESULTS. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMN AS INPUTS. EACH CASE CONTAINS ONLY ONE TYPE OF TEL IN ITS LAUNCH WAVE.

2. Track-while-scan Results

These results are very similar to those of the coordinated TBM launch arrival process. All but one of the 95 percent confidence intervals in Table 12 indicate that implementing a sensor with track-while-scan capability results in more successful TEL engagements on the average. The confidence interval for the 15 long-dwell TELs with the lognormal (30,5) parameters has an upper and lower bound equal to zero because both the baseline and track-while-scan models killed every TEL in the launch wave in all replications.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	3.4	0.16	[0.87, 1.45]
		30	3.0	0.12	[0.63, 1.13]
		45	3.0	0.13	[0.53, 1.07]
	(10,10)	15	3.7	0.24	[0.57, 1.07]
		30	4.4	0.24	[0.53, 1.19]
		45	4.4	0.29	[0.48, 1.32]
medium	(20,5)	15	13.7	0.19	[0.93, 1.51]
		30	14.5	0.27	[1.43, 2.21]
		45	14.2	0.25	[1.43, 2.17]
	(20,20)	15	8.6	0.30	[0.58, 1.14]
		30	11.5	0.34	[0.71, 1.33]
		45	12.8	0.33	[0.71, 1.61]
long	(30,5)	15	15.0	0.00	[0.00, 0.00]
		30	22.1	0.25	[0.77, 1.43]
		45	21.5	0.25	[1.14, 1.90]
	(30,20)	15	13.0	0.21	[0.49, 1.03]
		30	18.6	0.32	[0.94, 1.74]
		45	21.8	0.40	[1.62, 2.58]

TABLE 12. TRACK-WHILE-SCAN RESULTS FOR THE COORDINATED TEL STOP ARRIVAL PROCESS. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE TRACK-WHILE-SCAN AND BASELINE MOES. ALL BUT ONE OF THESE CONFIDENCE INTERVALS SUGGEST THAT THE TRACK-WHILE-SCAN SYSTEM PERFORMS STATISTICALLY BETTER THAN THE BASELINE SYSTEM IN TERMS OF MEAN NUMBER OF TELS KILLED. THERE IS NO IMPROVEMENT OR DEGRADATION FOR THE CASE CONSISTING OF 15 LONG-DWELL TELS WITH THE LOGNORMAL (30,5) DWELL TIME DISTRIBUTION BECAUSE BOTH THE BASELINE AND TRACK-WHILE-SCAN SYSTEMS WERE ABLE TO KILL EVERY TEL IN THE LAUNCH WAVE IN EVERY REPLICATION.

As with the coordinated TBM launch case, the track-while-scan model on the average reduces the time required to detect stopped TELs; however, these reductions are negated because it also induces congestion in the analyst queue.

3. LIFO Analyst Queue

Most of the 95 percent confidence intervals for the paired difference between the LIFO and baseline CONOPS MOEs in Table 13 either contain or are very close to zero. This indicates that the LIFO queue discipline has little effect on the mean number of TELs killed in a coordinated stop launch wave.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	**2.3**	**0.10**	[- 0.14, 0.26]
		30	**2.3**	**0.08**	[- 0.07, 0.31]
		45	**2.1**	**0.09**	[- 0.29, 0.17]
	(10,10)	15	**3.1**	**0.22**	[- 0.09, 0.41]
		30	**3.9**	**0.23**	[0.00, 0.68]
		45	**4.0**	**0.27**	[- 0.04, 1.04]
medium	(20,5)	15	**12.4**	**0.21**	[- 0.37, 0.21]
		30	**14.1**	**0.24**	**[0.92, 1.92]**
		45	**13.5**	**0.25**	**[0.47, 1.69]**
	(20,20)	15	**7.8**	**0.28**	[- 0.20, 0.28]
		30	**10.6**	**0.33**	[- 0.30, 0.46]
		45	**11.5**	**0.38**	[- 0.73, 0.49]
long	(30,5)	15	**15.0**	**0.02**	[- 0.06, 0.02]
		30	**20.5**	**0.22**	**[- 0.93, - 0.07]**
		45	**21.6**	**0.22**	**[1.06, 2.18]**
	(30,20)	15	**12.2**	**0.23**	[- 0.33, 0.17]
		30	**17.4**	**0.33**	[- 0.40, 0.64]
		45	**20.5**	**0.42**	**[0.08, 1.60]**

TABLE 13. LIFO ANALYST QUEUE RESULTS FOR COORDINATED TEL STOPS. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE LIFO CONOPS AND THE BASELINE MOES. FOR ALL CASES, THERE IS LITTLE OR NO STATISTICAL DIFFERENCE IN THE MEAN NUMBER OF TELS KILLED.

4. Updating

The argument for the updating CONOPS presented in the coordinated TBM launch sub-section of this chapter also applies to the coordinated TEL stop cases in this sub-section. That is, the TCS system should have the capability to abort the processing of those TELs whose dwell times have been observed by the sensor to have elapsed if updating does not limit the mean number of TELs killed.

a. Mean Number of TELs Engaged Prior to Dwell Time Completion

The updating CONOPS model produces results that are statistically equivalent to or slightly better than the baseline model for the mean number of TELs killed. Appendix A reports these results.

This implies that updating will be advantageous if it saves weapons.

b. Mean Number of Weapons Expended

The confidence intervals for the mean number of weapons saved in Table 14, along with the previous results for the mean number of TELs killed, suggests that the updating CONOPS has the potential to save many weapons without affecting the mean number of TELs killed. For example, refer to the case in Table 14 consisting of 45 short-dwell TELs with lognormal (10,10) dwell time distributions. The updating CONOPS is expected to save between 14 and 15 weapons, on average, when compared to the corresponding baseline case. This is significant considering that, for the same case, there is no statistical evidence that a difference exists in the mean number of TELs killed between the updating and baseline models.

As in the updating CONOPS for coordinated TBM launches, the same CONOPS here also tends to save more weapons as the size of the attack wave increases.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of weapons expended (MOE)	std error of MOE	95% confidence interval for expected number of weapons saved (MOE baseline system - MOE altered system)
short	(10,2)	15	**14.4**	**0.12**	**[0.36, 0.84]**
		30	**26.5**	**0.27**	**[3.01, 4.07]**
		45	**38.1**	**0.36**	**[6.16, 7.60]**
	(10,10)	15	**12.0**	**0.22**	**[2.58, 3.46]**
		30	**21.6**	**0.31**	**[7.82, 9.06]**
		45	**30.3**	**0.44**	**[13.86, 15.62]**
medium	(20,5)	15	**15.0**	**0.00**	[0.00, 0.00]
		30	**27.7**	**0.18**	**[1.91, 2.61]**
		45	**38.4**	**0.30**	**[6.04, 7.24]**
	(20,20)	15	**13.6**	**0.15**	**[1.06, 1.66]**
		30	**24.4**	**0.25**	**[5.14, 6.14]**
		45	**33.8**	**0.32**	**[10.55, 11.81]**
long	(30,5)	15	**15.0**	**0.00**	[0.00, 0.0]
		30	**29.9**	**0.04**	**[0.01, 0.19]**
		45	**42.5**	**0.19**	**[2.15, 2.93]**
	(30,20)	15	**14.7**	**0.09**	**[0.11, 0.45]**
		30	**27.3**	**0.18**	**[2.31, 3.05]**
		45	**37.5**	**0.31**	**[6.91, 8.17]**

TABLE 14. UPDATING CONOPS MEAN NUMBER OF WEAPONS EXPENDED AND MEAN NUMBER OF WEAPONS SAVED FOR COORDINATED TEL STOPS. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 SIMULATION REPLICATIONS USING THE LOGNORMAL DISTRIBUTION PARAMETERS AND THE NUMBER OF TELS IN THE SECOND AND THIRD COLUMNS AS INPUTS. THE 95% CONFIDENCE INTERVALS ARE FOR THE PAIRED DIFFERENCE BETWEEN THE UPDATING AND BASELINE MOES. HOWEVER, BECAUSE THE INTEREST HERE IS THE NUMBER OF WEAPONS SAVED, THE MOE FOR THE UPDATING CONOPS IS SUBTRACTED FROM THE MOE FOR THE BASELINE CONOPS. THE CONFIDENCE INTERVALS INDICATE THAT THE UPDATING CONOPS SAVES WEAPONS ON AVERAGE. FOR EXAMPLE, IN THE CASE CONSISTING OF 45 SHORT-DWELL TELS WITH LOGNORMAL (10,10) DWELL TIME DISTRIBUTIONS, THE UPDATING CONOPS SAVES, ON THE AVERAGE, BETWEEN 14 AND 15 WEAPONS WHEN COMPARED TO THE CORRESPONDING BASELINE CASE. THIS IS SIGNIFICANT CONSIDERING THAT THERE IS NO STATISTICAL EVIDENCE THAT A DIFFERENCE EXISTS IN THE MEAN NUMBER OF TELS KILLED BETWEEN THE TWO MODELS.

5. Priority Queues

a. New Baseline (All Queues FCFS)

TEL dwell types	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE
mixed	med: (20,5) long: (30,5)	15	**13.6**	**0.17**
		30	**16.3**	**0.33**
		45	**16.1**	**0.33**
	med: (20,20) long: (30,20)	15	**9.7**	**0.30**
		30	**13.2**	**0.40**
		45	**14.8**	**0.47**

TABLE 15. PRIORITY QUEUE BASELINE RESULTS FOR COORDINATED TEL STOPS. ALL QUEUES ARE FCFS FOR THE BASELINE MODEL. EACH MEAN AND STANDARD ERROR FOR THE MOE IS BASED ON 50 REPLICATIONS FOR A MIX OF MEDIUM AND LONG-DWELL TELS WITH THE DISTRIBUTION PARAMETERS IN THE SECOND COLUMN. EACH TEL TYPE IS GENERATED INDEPENDENTLY WITH PROBABILITY 0.5 AND THE TOTAL NUMBER AGREES WITH THE NUMBER OF TELS IN THE THIRD COLUMN.

b. Prioritize on Medium-Dwell TELs

Prioritizing on medium-dwell TELs does not significantly improve upon baseline performance at the 5 percent level of significance. These results are summarized in Appendix A

c. Prioritize on Long-Dwell TELs

The 95 percent confidence intervals for the paired difference between the prioritize on long-dwell TEL and baseline mean FCFS CONOPS MOEs in Table 16 either contain or are very close to zero. This indicates that prioritizing on long-dwell TELs has little effect on the mean number of TELs killed in a coordinated stop launch wave.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
mixed	med: (20,5) long: (30,5)	15	**13.5**	**0.18**	[- 0.35, 0.15]
		30	**16.4**	**0.24**	[- 0.45, 0.65]
		45	**16.9**	**0.28**	**[0.21, 1.35]**
	med: (20,20) long: (30,20)	15	**9.5**	**0.30**	[- 0.45, 0.05]
		30	**13.7**	**0.36**	[- 0.03, 1.07]
		45	**15.4**	**0.50**	**[0.03, 1.25]**

TABLE 16. PRIORITY QUEUE LONG-DWELL TEL PRIORITIZATION RESULTS FOR COORDINATED TEL STOPS. EACH MEAN AND STANDARD ERROR OF THE MOE IS BASED ON 50 REPLICATIONS FOR A MIX OF MEDIUM AND LONG-DWELL TELS WITH THE DISTRIBUTION PARAMETERS IN THE SECOND COLUMN. EACH TEL TYPE IS GENERATED INDEPENDENTLY WITH PROBABILITY 0.5 AND THE TOTAL NUMBER AGREES WITH THE NUMBER OF TELS IN THE THIRD COLUMN. IN BOTH CASES THAT CONSIST OF 45 TELS, PRIORITIZING ON LONG-DWELL TELS RESULTS IN ABOUT ONE ADDITIONAL KILL ON THE AVERAGE.

G. DISCUSSION

1. Sensitivity of the Results to the Standard Deviation of TEL Dwell Times

Three external noise factors drive the simulation results for each system examined in this thesis. *External noise factors* are outside sources of variability that cannot be controlled during normal operations of the system and affect system performance (reference 12). The first factor is the distribution of TEL stops in a launch wave. The second is the size of launch wave. These first two factors determine the amount of load placed on the TCS system. For example, if all TELs in a large attack wave stop within a short time interval, the TCS system will become congested and TEL processing times will tend to increase as the system sequentially engages them. However, if all TEL stops are uniformly spread out over a large time interval or the number of TELs in an attack wave is small, the Blue engagement system will be less congested and TEL processing times will tend to be similar for all engaged TELs. The third external factor is the dwell time distribution of the TELs in a launch wave. Because this thesis assumes that a TEL is vulnerable to attack only during its dwell time, this factor determines the amount of time available to execute the kill chain before a successful engagement opportunity is lost.

Together, these external noise factors play an integral role in understanding the impact of dwell time standard deviation on the simulation results. This discussion is limited to the baseline CONOPS for the two TEL arrival processes where all launch waves consist of same-type TELs.

The coordinated stop cases assume that all TEL stops are uniformly distributed within a five-minute time interval. In addition, common random numbers ensure that all TEL stops and the corresponding processing times are identical for equal sized launch waves. As a result, the total time to process and engage each stopped TEL in waves of equal size may be compared to the dwell time survivor functions for those TEL dwell time distributions that share the same mean but different standard deviations. The *survivor function evaluated at time t of a nonnegative random variable X, $R(t)$*, is the probability that an observed value of the random variable X is at least (survives) some value t; that is $R(t)=P(X \geq t)$, where the random variable X is a TEL dwell time and t is the time a weapon arrives at the TEL after it stops (reference 11). The survivor functions are used to approximate the probability of a successful TEL engagement within a coordinated TEL stop launch wave. These probabilities will help determine the dwell time distribution against which the system may perform better in terms of the MOEs.

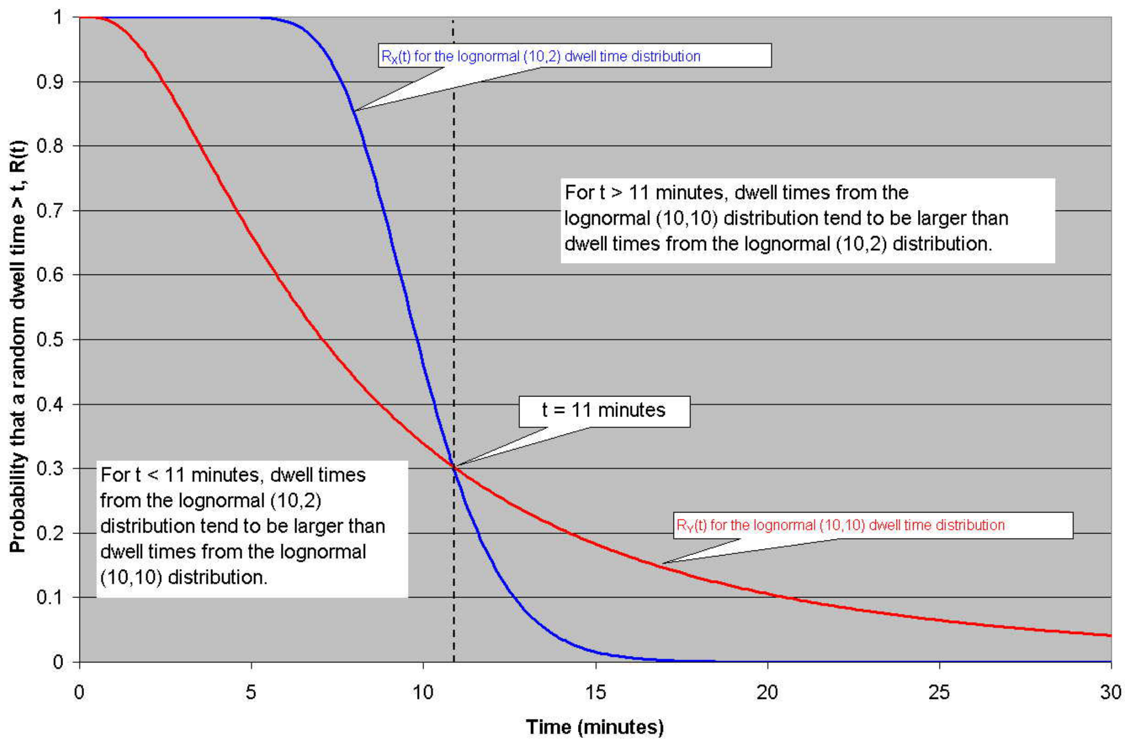

FIGURE 10. SHORT-DWELL TEL SURVIVOR FUNCTIONS. THE SURVIVOR FUNCTION FOR EACH SHORT-DWELL TEL DISTRIBUTION AT TIME T IS THE PROBABILITY THAT A RANDOMLY DRAWN DWELL TIME FROM THE DISTRIBUTION WILL BE GREATER THAN OR EQUAL TO TIME t ON THE X-AXIS; THAT IS AND $R_Y(t) = P(Y \geq t))$. A VALUE ON THE X-AXIS CAN BE THOUGHT OF AS THE TIME TO COMPLETE A TEL ENGAGEMENT AFTER THE TEL STOPS. THEREFORE, GIVEN THE ARRIVAL TIME t OF A WEAPON AT THE TEL LOCATION, $R_X(t)$ AND $R_Y(t)$ ARE THE PROBABILITIES THAT THE TEL IS KILLED. FOR $t < 11$, $R_X(t) > R_Y(t)$ IMPLIES THAT TEL DWELL TIMES FROM THE LOGNORMAL (10,2) DISTRIBUTION TEND TO BE LARGER THAN TEL DWELL TIMES FROM THE LOGNORMAL (10,10) DISTRIBUTION (REFERENCE 8). THE OPPOSITE IS TRUE FOR $t > 11$.

Let N be the number of same-type TELs in each replication of a simulated coordinated stop attack wave. There are R replications. For each replication, TEL engagements are numbered according to the order in which they occur. The first engagement is number 1 and the last engagement is N. Let $t_{i,r}$ be the time from when the i^{th}

engaged TEL stops until the assigned weapon arrives at the TEL's location for replication r (the TEL may have departed). Let $x_{i,r} = R(t_{i,r})$ be the probability that the i^{th} engaged TEL is killed in the r^{th} replication. An estimate of the probability the i^{th} engaged TEL is killed is $\hat{p}_i = \frac{1}{R}\sum_{r=1}^{R} x_{i,r}$. The estimated $\hat{p}_i$'s are then used to estimate the expected number of TELs killed in a launch wave.

Let S_i = 1 if the i^{th} engaged TEL in a launch wave is killed and let S_i = 0 if the i^{th} engaged TEL is lost. Then, the estimated probability that S_i = 1 is $\hat{p}_i$, and the estimated probability that S_i = 0 is $1-\hat{p}_i$. Because the expected value of a sum of random variables is the sum of the expected values, whether or not the random variables are independent, an estimate of the expected number of TELs killed in a launch wave is $\hat{Y} = \sum_{i=1}^{n} \hat{p}_i$.

Figures 11 and 12 plot the estimated kill probabilities for each TEL engagement ($\hat{p}_i$'s) for the baseline simulation with 50 replications. The figures also display the estimated expected number of TELs killed in the launch wave ($\hat{Y}$).

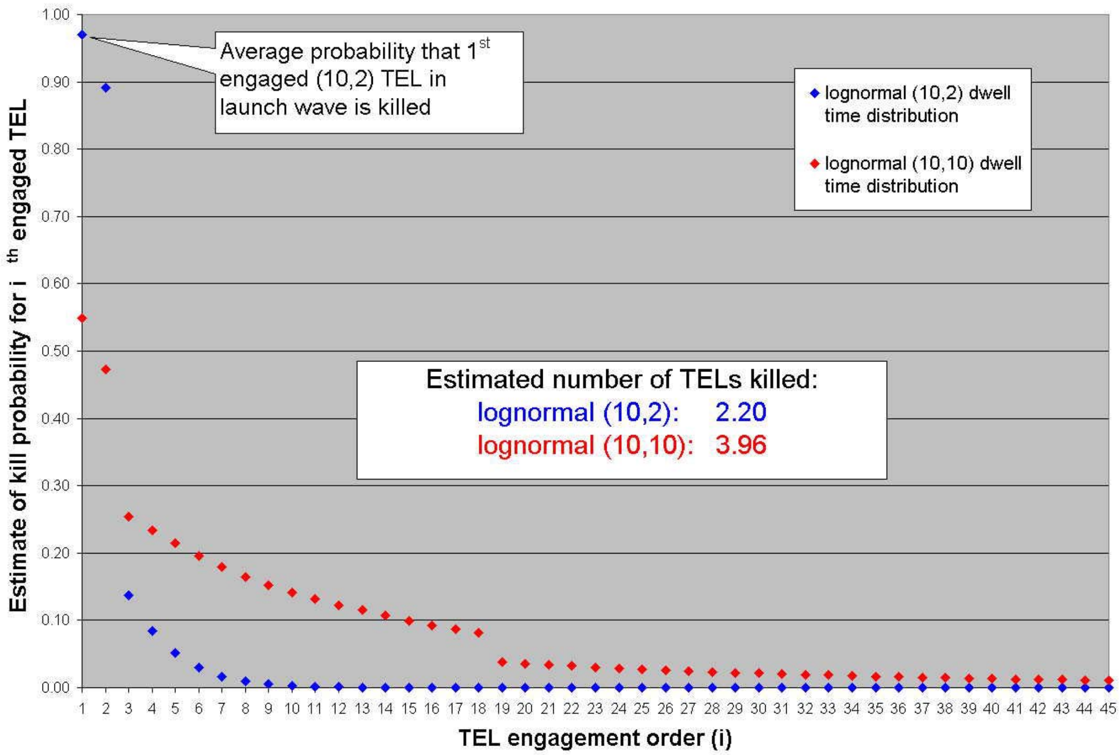

FIGURE 11. EFFECT OF DWELL TIME STANDARD DEVIATION ON SHORT-DWELL TEL ENGAGEMENTS. THIS FIGURE PLOTS THE ESTIMATED KILL PROBABILITIES OF 45 TELS IN A COORDINATED STOP LAUNCH WAVE FOR EACH SHORT-DWELL TEL DISTRIBUTION. KILL PROBABILITY ESTIMATES ARE FOR THE BASELINE SIMULATION WITH 50 REPLICATIONS. EACH OF THE ESTIMATED KILL PROBABILITIES OF THE FIRST TWO TEL ENGAGEMENTS FOR THE LOGNORMAL DISTRIBUTION WITH THE SMALLER STANDARD DEVIATION ARE HIGHER THAN EACH OF THE ESTIMATED KILL PROBABILITES OF THE FIRST TWO TEL ENGAGEMENTS FOR THE LOGNORMAL DISTRIBUTION WITH THE LARGER STANDARD DEVIATION. AFTER THE FIRST TWO ENGAGEMENTS, HOWEVER, THE ESTIMATED KILL PROBABILITIES ARE HIGHER FOR THE LOGNORMAL DISTRIBUTION WITH THE LARGER STANDARD DEVIATION. THE ESTIMATED EXPECTED NUMBER OF TELS KILLED IN THE LAUNCH WAVE FOR EACH DWELL TIME DISTRIBUTION IS OBTAINED BY SUMMING THE ESTIMATED KILL PROBABILITIES. THE ESTIMATED NUMBER OF TELS KILLED IS HIGHER FOR THE SHORT-DWELL TEL DISTRIBUTION WITH THE LARGER STANDARD DEVIATION.

Refer to Table 11. For a given number of short-dwell TELs that coordinate their stop times and the calculated MOE, mean number of TELS killed, the baseline system performs statistically better for the dwell time distribution with a standard deviation of 10 minutes when compared to the distribution with a standard deviation of 2 minutes. Figure 11 supports the simulation results reported in Table 11 for the case that consists of 45 short-dwell TELs.

Again, refer to Table 11. For a given number of medium-dwell TELs that coordinate their stop times and the calculated MOE, mean number of TELS killed, the baseline system performs statistically better for the dwell time distribution with a standard deviation of 5 minutes. The results in Figure 12 agree with those in Table 11. These qualitative results also hold for system performance against long-dwell TELs.

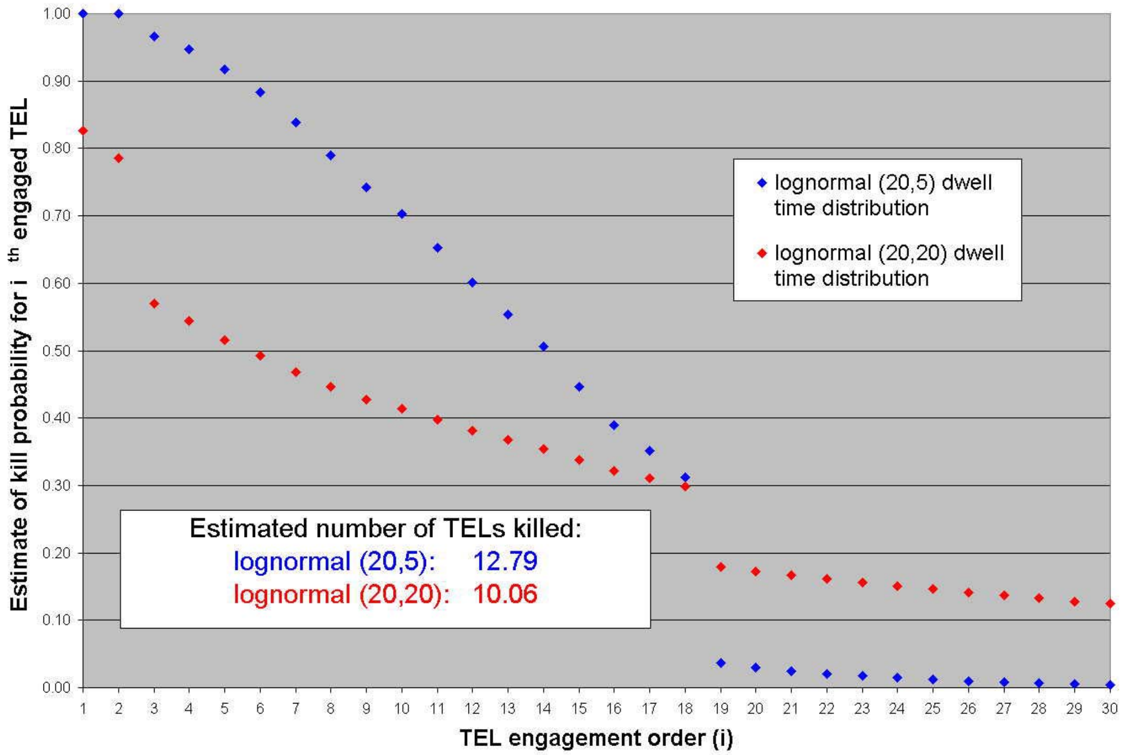

FIGURE 12. EFFECT OF DWELL TIME STANDARD DEVIATION ON MEDIUM-DWELL TEL ENGAGEMENTS. THIS FIGURE PLOTS THE ESTIMATED KILL PROBABILITIES OF 30 TELS IN A COORDINATED STOP LAUNCH WAVE FOR EACH MEDIUM-DWELL TEL DISTRIBUTION. KILL PROBABILITY ESTIMATES ARE FOR THE BASELINE SIMULATION WITH 50 REPLICATIONS. EACH OF THE ESTIMATED KILL PROBABILITIES OF THE FIRST 18 TEL ENGAGEMENTS FOR THE LOGNORMAL DISTRIBUTION WITH THE SMALLER STANDARD DEVIATION ARE HIGHER THAN EACH OF THE ESTIMATED KILL PROBABILITES OF THE FIRST 18 TEL ENGAGEMENTS FOR THE LOGNORMAL DISTRIBUTION WITH THE LARGER STANDARD DEVIATION. AFTER THE FIRST 18 ENGAGEMENTS, HOWEVER, THE ESTIMATED KILL PROBABILITIES ARE HIGHER FOR THE LOGNORMAL DISTRIBUTION WITH THE LARGER STANDARD DEVIATION. THE ESTIMATED EXPECTED NUMBER OF TELS KILLED IN THE LAUNCH WAVE FOR EACH DWELL TIME DISTRIBUTION IS OBTAINED BY SUMMING THE ESTIMATED KILL PROBABILITIES. THE ESTIMATED NUMBER OF TELS KILLED IS HIGHER FOR THE MEDIUM-DWELL TEL DISTRIBUTION WITH THE SMALLER STANDARD DEVIATION.

A general conclusion for the baseline system and TELs employing coordinated stop tactics is that given two lognormal dwell time distributions that differ only in standard deviation, the expected number of TELs killed will tend to be higher for the dwell time distribution with the smaller standard deviation if, for all TELs in the launch wave, the average time to complete an engagement after a TEL stops is less than the time at which the survivor functions intersect. The converse is true if, for all TELs in the launch wave, the average time to complete each engagement is greater than the time at which the survivor functions intersect. For the cases studied, however, the times to complete engagements after the TELs stop within a single launch wave occur on both sides of the intersection of the survivor functions. As a result, it is necessary to estimate the kill probabilities of each TEL engagement using the survivor function of each dwell time distribution and then sum the kill probabilities in order to estimate the expected number of TELs killed.

The approach applied above is not valid for the coordinated TBM launch cases because two of the external noise factors, the TEL dwell times and the TEL stop times, are dependent. Recall that all TBM launches are assumed to occur within a five-minute window and that each TEL's stop time is obtained by subtracting half of its randomly drawn dwell time from its random launch time. This derivation of TEL stop times has two important implications. First, dwell times affect the rate at which TELs stop (enter the TCS system). Therefore, the distribution of TEL stop times and the corresponding processing times are dependent on the dwell time distribution, even though common random numbers are used. Secondly, the TELs in a launch wave tend to stop in descending order of their dwell times. As a result, TEL loss times for the coordinated TBM launch cases also depend on the order in which the TELs are engaged. That is, the dwell times of the last TELs engaged by the system tend to be smaller than those of the first TELs engaged. Therefore, each engaged TEL has a unique loss time distribution that depends on the original dwell time distribution and the size of the launch wave. Figure 13 illustrates how dwell time standard deviation affects mean TEL engagement and loss times.

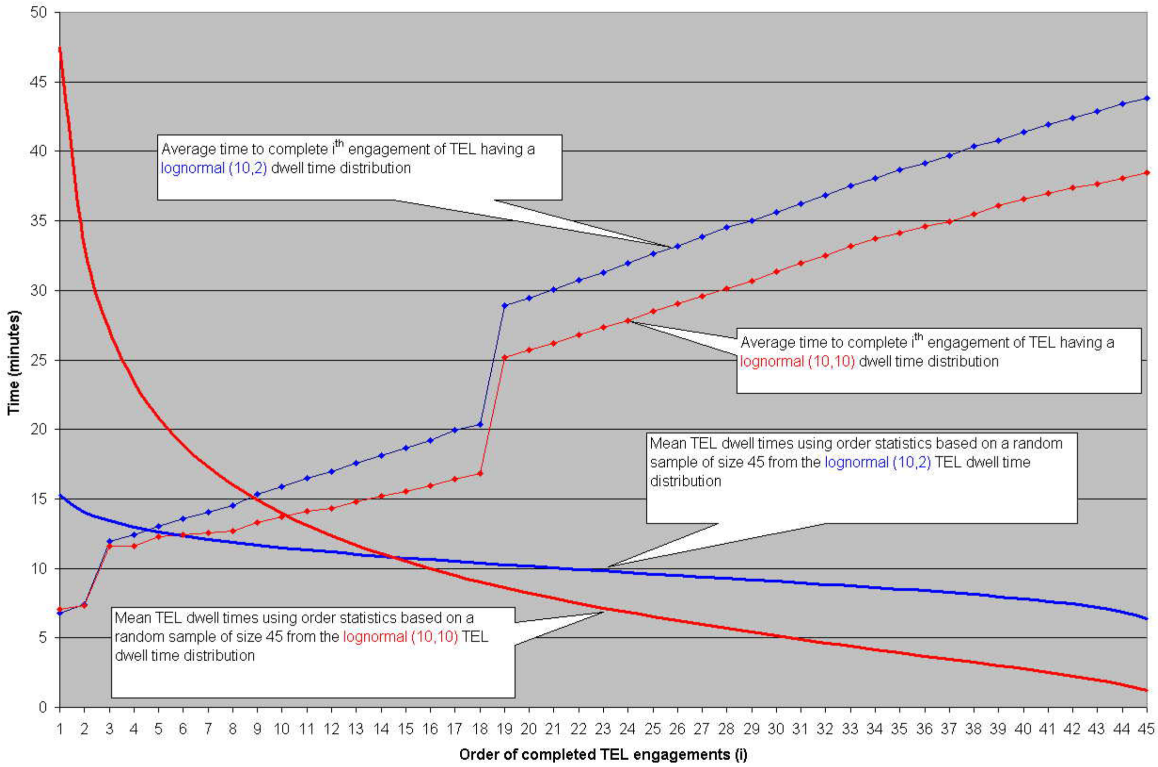

FIGURE 13. EFFECT OF DWELL TIME STANDARD DEVIATION ON AVERAGE SHORT-DWELL TEL ENGAGEMENT AND LOSS TIMES FOR A COORDINATED TBM LAUNCH. THIS FIGURE PLOTS THE AVERAGE BASELINE TIMES TO COMPLETE ENGAGEMENTS AFTER THE TELS STOP AND AVERAGE TEL DWELL TIMES FOR 45 TELS IN A SPECIAL CASE OF COORDINATED LAUNCHES WHERE ALL TBMS ARE FIRED SIMULTANEOUSLY. MEAN DWELL TIMES ARE OBTAINED ANALYTICALLY FROM ORDER STATISTICS BASED ON A RANDOM SAMPLE OF SIZE 45 (THE NUMBER OF TELS IN THE LAUNCH WAVE). THE AVERAGE DWELL TIME OF THE FIRST ENGAGED TEL IS AN ESTIMATE OF THE ANALYTIC MEAN FOR THE LARGEST ORDER STATISTIC (APPENDIX D). THE AVERAGE DWELL TIME OF THE 45TH ENGAGED TEL IS AN ESTIMATE OF THE ANALYTIC MEAN FOR THE SMALLEST ORDER STATISTIC. THE LINES ARE PLOTTED OVER THE MEANS OF THE 45 ORDER STATISTICS TO SHOW THE TREND OF DECREASING MEAN DWELL TIMES AS TELS ARE ENGAGED. THE MEAN TIMES TO COMPLETE ENGAGEMENTS AFTER THE TELS STOP ARE ESTIMATES BASED ON 50 SIMULATION REPLICATIONS. THE AVERAGE TIMES TO COMPLETE ENGAGEMENTS ARE HIGHER FOR THE LOGNORMAL DWELL TIME DISTRIBUTION WITH A STANDARD DEVIATION OF 2 MINUTES BECAUSE ALL TELS STOP IN A SMALLER TIME INTERVAL WHICH RESULTS IN CONGESTION AND LONGER AVERAGE ENGAGEMENT TIMES.

Obtaining the empirical survivor function for each TEL engagement requires the use of order statistics and is beyond the scope of this thesis. However, Figure 13 should give the reader an intuitive understanding of the sensitivity of the results to dwell time standard deviation for the coordinated TBM launch cases.

To generalize the coordinated TBM launch case, TELs tend to stop in decreasing order of dwell time if all TBM launches occur during a short time interval. This effect diminishes as the TBM launch window becomes longer. In addition, larger dwell time standard deviations result in longer time intervals within which all TELs stop. As the times between TEL stops become larger, sequential processing delays may diminish because congestion becomes less of an issue. However, these savings in processing times may be offset by the decreasing times until loss of the TELs in the launch wave.

2. Sensitivity of the Results to the TEL Arrival Processes

Generally, the TCS system performs better in terms of the estimated expected number of TELS killed against coordinated TBM launches than coordinated TEL stops because the initial processing times tend to be similar and the initial dwell times tend to be higher for coordinated TBM launches than for coordinated TEL stops. This is an artifact of the representation of the TEL arrival processes and the detection of the TELS. In the coordinated launch case, the dwell times for the last targets engaged tend to be smaller than the dwell times of the first targets engaged. This effect would be diminished if the time interval during which all TELs fire their TBM were increased. In both cases, for the target arrival process represented here, the processing times for TELs engaged later in a launch wave will tend to be larger than those for the earlier engaged targets.

These arrival processes are important considerations for developing balanced active TCS and reactive theater ballistic missile defense (TBMD) systems. However, it is important to restate that TBM launch times are arbitrarily chosen to occur at the midpoint of each TEL’s dwell time. In reality, this will not be the case and different distributions of order statistics will result from the coordinated TBM launch cases.

3. Sensitivity of the Results to the Shooter Selection Policy

Mach 4 weapons launched from a range of 500 nmi are relatively ineffective in all cases studied in this thesis because of their long fly-out times, the shooter selection policy, and congestion induced processing delays. Although these 500 nmi weapons are surface-launched in this thesis, the results would have been the same if the weapons had been launched from another shooter platform at the same range. The 500 nmi flight time for a Mach 4 weapon is approximately 13 minutes. Further, the surface shooter does not engage any TELs until the two UCAV and 16 CAP weapons are expended on the first 18 TELs engaged. Under the current shooter selection policy, the mean time to engage a TEL after it stops tends to be larger than the mean remaining dwell time after 22 targets have been engaged for the coordinated TBM launch cases that consist of long-dwell TELs. Figure 14 illustrates why surface-launched weapons are ineffective under the implemented shooter selection policy for the case of coordinated TBM launches consisting of long-dwell TELs. Figure 14 also suggests that adopting a different shooter selection policy may be better. This, however, is beyond the scope of this thesis and is recommended as a topic for further research.

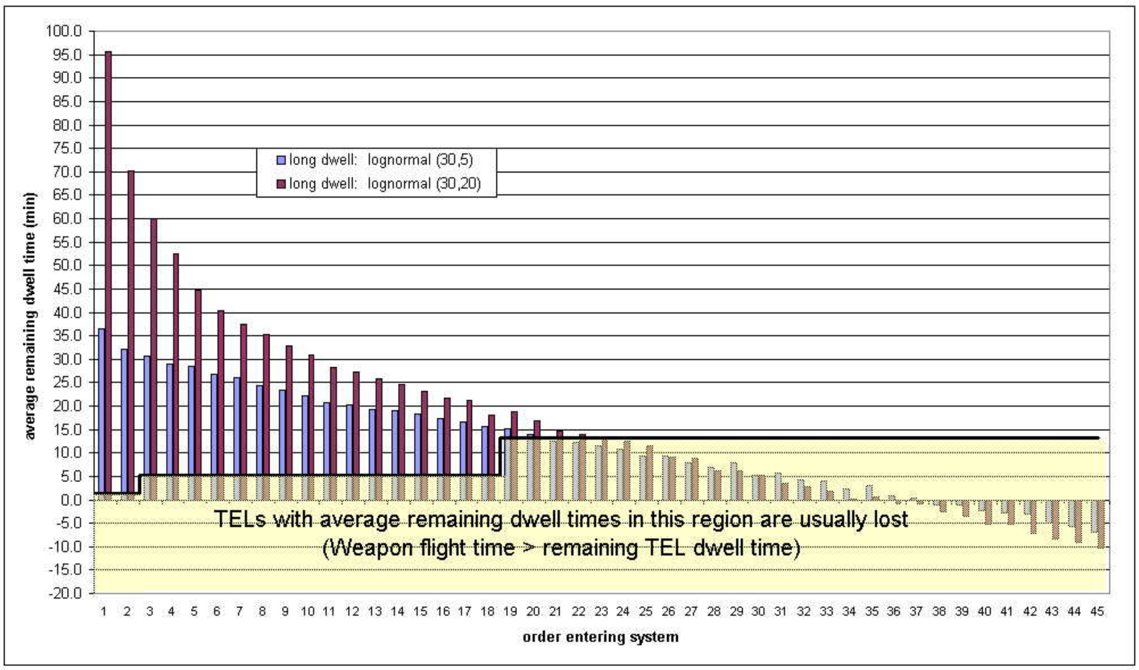

FIGURE 14. AVERAGE REMAINING DWELL TIME WHEN A SHOOTER PLATFORM IS SELECTED TO ENGAGE THE TEL. AVERAGE REMAINING DWELL TIME FOR BOTH LONG-DWELL TEL DISTRIBUTIONS ARE BASED ON BASELINE COORDINATED LAUNCH SIMULATIONS CONSISTING OF 45 TELS AND 30 REPLICATIONS. THE UPPER BOUNDARY OF THE SHADED REGION DENOTES THE WEAPON FLIGHT TIME. THE UPPER BOUNDARY HAS THREE LEVELS THAT CORRESPOND TO THE AVAILABLE WEAPONS IN THE SIMULATION. THE LOWER, MIDDLE, AND UPPER LEVELS REFER TO THE FLIGHT TIMES REQUIRED FOR THE TWO 50 NMI UCAV WEAPONS, 16 CAP WEAPONS, AND 100 SURFACE WEAPONS, RESPECTIVELY. THE BASELINE SYSTEM CAN USUALLY ENGAGE THOSE TELS HAVING AVERAGE REMAINING DWELL TIMES ABOVE THE SHADED REGION. THE SYSTEM CAN ONLY PROCESS ABOUT 35 TELS, ON AVERAGE, BEFORE THE DWELL TIMES COMPLETELY EXPIRE.

4. Congestion in the TCS Architecture

Figure 5 implies that mean waiting times in the image analyst queue increase with the number of TELs in a launch wave. The simulations are run with an additional analyst, but the results do not improve significantly. This is because the queues in the decision and coordinate mensuration phases grow at a rate such that the total amount of time required to complete image analysis and coordinate registration changes very little. This demonstrates the intricacies of the network of queues within the proposed TCS architecture.

Similarly, when track-while-scan capability is introduced to the baseline model, 5 to 10 minute reductions in the mean time to detect stopped TELs are common, depending on the number of TELs in the launch wave. However, these benefits are negated by increased mean waiting times in the SAR and image analyst queues.

Although not directly addressed in this thesis, the results imply that the system is very sensitive to TEL decoys. Figure 14 illustrates that, on average, only 36 of the 45 long-dwell TELs in a coordinated launch wave are still stationary when the TCS system selects any shooter platform to engage the detected target with a high-speed weapon. Because of this, the GMTI and SAR sensors need to have low rates of false detections so that additional congestion may be avoided. It could also be that imperfect detection might be useful in a scenario where there is heavy non-target traffic because it may decrease the arrival rate to the server. However, imperfect detection can also delay detection of TELS.

For the assumptions of this thesis in the cases studied, Mach 4 high-speed weapons launched from ranges greater than 500 nmi are not effective under the current shooter selection policy. Therefore, image analysts must be able to effectively distinguish decoys from actual threats so that the close-range UCAV and CAP weapons are not wasted on decoys.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The most promising alternatives to the NAVAIR baseline TCS architecture and CONOPS explored in this thesis are the development of a track-while-scan GMTI and SAR sensor suite that is capable of operating in both radar modes simultaneously, and the adoption of a policy that allows the TCS architecture to update the movement status of TELs currently in the system. Neither the baseline nor any of the proposed alternatives enable the proposed TCS architecture to successfully engage short-dwell TELs consistently.

In terms of the mean number of TELs killed MOE, the track-while-scan system performs statistically better than the baseline against large coordinated TBM launch and coordinated stop attack waves of the surrogate TBM TELs used in this thesis. The time required by the GMTI radar to detect stopped TELs decreases between five and ten minutes for launch waves consisting of at least 30 TELs. However, the net reduction in the TCS kill chain is usually between 2 to 3 minutes, on average, because faster detections induce congestion in the image analysis phase. If another image analyst is added, delays in the decision and mensuration phase limit the net reduction. This stovepipe makes it very difficult to improve system performance and demonstrates the intricacy of the network of queues within the proposed TCS architecture.

Updating the movement status of stationary TELs while they are processed does not significantly affect the mean number of TELs killed, when compared to the baseline TCS

CONOPS, under its current implementation. However, for large launch waves, it does enable the system to successfully engage the same number of TELs with fewer missiles on average.

Although not directly addressed in this thesis, the results imply that the system is very sensitive to TEL decoys. This is because the mean cumulative processing delays, excluding weapon time of flight, exceed the mean dwell times for TELs in the latter stages of a large launch wave.

Long-range high-speed weapons, such as the 500 nmi surface weapons, are ineffective against the TBM TELs for the closest shooter with available weapons selection policy and assumptions adopted in this thesis. Because the shooter platform having a weapon with shortest fly-out time is always selected to engage a target, mean remaining dwell times for most of the TELs still in the system after all UCAV and CAP weapons have been expended are less than the long range weapon’s 13-minute flight time.

Alternative queueing disciplines such as LIFO and priority are ineffective for the coordinated TBM launch tactic because the system processes and engages TELs in nearly descending order of dwell times, regardless of TEL type. They do show limited success in the coordinated TEL stop case.

The results in this thesis are sensitive to the TEL arrival processes. Generally, the TCS system performs better against coordinated TBM launches than coordinated TEL stops because the initial processing times tend to be similar and the initial dwell times tend to be higher for coordinated TBM launches than for coordinated TEL stops. This is an artifact of the representation of the TEL arrival processes and the detection of the TELS.

B. RECOMMENDATIONS FOR FOLLOW-UP RESEARCH

This thesis addresses several alternative TCS CONOPS and a track-while-scan capability. However, it does not explore combinations of these alternatives against different sets of assumptions. A future topic for research may be to use a robust design approach in order to develop a more effective TCS architecture that is not sensitive to threat assumptions. The goal of the resulting TCS architecture should be closely tied to TBMD capabilities. The complete system that emerges will be a guide as to where investment dollars should be allocated for overall system improvements.

This thesis adopts a closest shooter with available weapons selection policy for the engagement phase of the kill chain. However, rough analysis indicates that this may not be the best selection policy for the arrival processes considered and the perfect knowledge assumed. However, if there were only one or a few TELS, selection of the closest shooter might be best. Therefore, alternative shooter selection policies should be investigated in more detail for multiple TEL arrival processes.

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APPENDIX A. OMMITTED ANALYSIS TABLES

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	**2.8**	**0.13**	[- 0.17, 0.21]
		30	**2.8**	**0.14**	[- 0.06, 0.34]
		45	**2.8**	**0.12**	[- 0.24, 0.20]
	(10,10)	15	**4.3**	**0.22**	[- 0.15, 0.11]
		30	**7.0**	**0.27**	[- 0.33, 0.09]
		45	**9.0**	**0.32**	[- 0.44, 0.12]
medium	(20,5)	15	**12.8**	**0.20**	[- 0.14, 0.42]
		30	**14.9**	**0.28**	[- 0.74, 0.26]
		45	**15.9**	**0.22**	[- 0.64, 0.24]
	(20,20)	15	**8.1**	**0.25**	[- 0.19, 0.07]
		30	**13.8**	**0.31**	[- 0.36, 0.24]
		45	**17.0**	**0.24**	**[- 0.62, - 0.14]**
long	(30,5)	15	**15.0**	**0.00**	[0.00, 0.00]
		30	**19.1**	**0.20**	**[- 0.89, - 0.15]**
		45	**20.5**	**0.23**	[- 0.86, 0.06]
	(30,20)	15	**13.2**	**0.21**	[- 0.09, 0.05]
		30	**18.6**	**0.20**	**[- 0.57, - 0.11]**
		45	**22.3**	**0.39**	[- 0.77, 0.05]

LIFO Results for Coordinated TBM Launches. Each mean and standard error of the MOE is based on 50 simulation replications using the lognormal parameters and the number of TELs in the second and third columns as inputs. The 95% confidence intervals are for the paired difference between the LIFO and baseline MOEs. The confidence intervals indicate that the LIFO system performs either statistically equivalent to or worse than the baseline system in terms of the mean number of TELs killed.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	**2.5**	**0.11**	**[- 0.35, - 0.05]**
		30	**2.7**	**0.12**	[- 0.11, 0.11]
		45	**2.8**	**0.13**	[- 0.21, 0.17]
	(10,10)	15	**4.2**	**0.23**	[- 0.18, 0.06]
		30	**7.0**	**0.29**	[- 0.26, 0.10]
		45	**9.2**	**0.32**	[- 0.09, 0.29]
medium	(20,5)	15	**12.7**	**0.20**	[0.00, 0.00]
		30	**15.4**	**0.22**	[- 0.09, 0.65]
		45	**16.1**	**0.18**	[- 0.32, 0.36]
	(20,20)	15	**8.2**	**0.24**	[- 0.02, 0.22]
		30	**14.0**	**0.26**	[- 0.08, 0.32]
		45	**17.3**	**0.20**	[- 0.10, 0.10]
long	(30,5)	15	**15.0**	**0.00**	[0.00, 0.00]
		30	**19.7**	**0.21**	[0.00, 0.00]
		45	**20.7**	**0.21**	[- 0.55, 0.07]
	(30,20)	15	**13.2**	**0.21**	[0.00, 0.00]
		30	**18.9**	**0.17**	[- 0.18, 0.10]
		45	**22.9**	**0.38**	[- 0.07, 0.55]

Updating Results for the Mean Number of TELs Killed for Coordinated TBM Launches. Each mean and standard error of the MOE is based on 50 simulation replications using the lognormal parameters and the number of TELs in the second and third columns as inputs. The 95% confidence intervals are for the paired difference between the updating and baseline MOEs. All but one of the confidence intervals indicate that the updating system performs statistically equivalent to the baseline system in terms of the mean number of TELs killed.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of mean	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	**2.2**	**0.11**	[- 0.02, 0.06]
		30	**2.2**	**0.08**	[- 0.11, 0.11]
		45	**2.2**	**0.08**	[- 0.15, 0.07]
	(10,10)	15	**3.0**	**0.23**	[- 0.07, 0.19
		30	**3.9**	**0.25**	**[0.11, 0.49]**
		45	**3.7**	**0.28**	[- 0.02, 0.38]
medium	(20,5)	15	**12.4**	**0.22**	[0.00, 0.00]
		30	**12.8**	**0.26**	[- 0.33, 0.45]
		45	**12.6**	**0.27**	[- 0.09, 0.49]
	(20,20)	15	**7.7**	**0.29**	[- 0.14, 0.14]
		30	**10.6**	**0.33**	[- 0.07, 0.39]
		45	**11.6**	**0.35**	[- 0.26, 0.26]
long	(30,5)	15	**15.0**	**0.00**	[0.00, 0.00]
		30	**20.9**	**0.23**	[- 0.15, 0.11]
		45	**20.0**	**0.20**	[- 0.36, 0.32]
	(30,20)	15	**12.3**	**0.22**	[- 0.09, 0.17]
		30	**17.3**	**0.35**	[- 0.36, 0.40]
		45	**19.8**	**0.42**	[-0.15, 0.43]

Updating Results for the Mean Number of TELs Killed for Coordinated TEL Stops. Each mean and standard error of the MOE is based on 50 simulation replications using the lognormal parameters and the number of TELs in the second and third columns as inputs. The 95% confidence intervals are for the paired difference between the updating and baseline MOEs. All but one of the confidence intervals indicate that the updating system performs statistically equivalent to the baseline system in terms of the mean number of TELs killed.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
mixed	med: (20,5) long: (30,5)	15	**13.8**	**0.19**	[- 0.03, 0.35]
		30	**16.3**	**0.25**	[- 0.52, 0.52]
		45	**16.7**	**0.32**	[- 0.03, 1.23]
	med: (20,20) long: (30,20)	15	**9.6**	**0.32**	[- 0.30, 0.26]
		30	**13.1**	**0.39**	[- 0.56, 0.52]
		45	**15.0**	**0.52**	[- 0.43, 0.83]

Prioritization on Medium-Dwell TELs Results on the Mean Number of Successful Engagements for Coordinated TEL Stops. Each mean and standard error for the MOE is based on 50 simulation replications using the lognormal parameters and the number of TELs in the second and third columns as inputs. All of the 95% confidence intervals contain zero. As a result, the prioritization of medium-dwell-TEL CONOPS performs statistically equivalent to the baseline in terms of the mean number of TELs killed.

APPENDIX B. MEANS, STANDARD DEVIATIONS, AND 95 PERCENT CONFIDENCE INTERVALS FOR FIGURES

Order of TEL	GMTI		SAR		Analyst		Decide		Total	
engagements	mean	stDev	mean	stDev	mean	stDev	mean	stDev	mean	stDev
1	4.1	0.94	0.3	0.00	0.8	0.16	0.8	0.47	6.0	1.11
2	3.9	1.03	0.4	0.14	1.0	0.32	0.8	0.47	6.1	0.90
3	4.3	0.99	0.5	0.23	1.2	0.46	0.8	0.38	6.8	0.88
4	4.5	1.20	0.6	0.28	1.4	0.53	0.8	0.38	7.3	0.91
5	4.6	0.99	0.8	0.32	1.5	0.56	0.8	0.39	7.8	0.73
6	4.6	1.09	1.0	0.38	1.9	0.67	0.9	0.50	8.3	0.90
7	4.7	1.15	1.1	0.44	2.1	0.80	0.9	0.49	8.8	0.96
8	5.1	1.39	1.1	0.58	2.2	0.88	0.9	0.44	9.4	0.94
9	5.1	1.35	1.3	0.62	2.6	0.95	1.1	0.71	10.1	1.12
10	4.9	1.41	1.5	0.65	2.9	0.97	1.2	0.77	10.6	1.12
11	5.5	1.48	1.4	0.73	3.1	0.96	1.3	0.81	11.3	1.24
12	5.3	1.50	1.6	0.76	3.5	0.97	1.3	0.80	11.7	1.39
13	5.5	1.66	1.7	0.84	3.8	0.94	1.3	0.89	12.3	1.39
14	5.8	1.61	1.7	0.88	4.1	0.95	1.4	1.01	12.9	1.52
15	5.8	1.73	1.8	0.93	4.3	1.04	1.4	0.90	13.3	1.32
16	6.5	1.87	1.7	1.04	4.5	1.24	1.4	0.84	14.0	1.46
17	6.5	1.86	1.8	1.04	4.9	1.23	1.4	0.82	14.6	1.43
18	7.0	1.90	1.7	1.10	5.1	1.08	1.3	0.72	15.1	1.51
19	7.2	1.98	1.8	1.14	5.4	1.06	1.2	0.72	15.6	1.35
20	7.1	1.88	2.0	1.15	5.8	1.09	1.3	0.79	16.2	1.44
21	7.7	1.95	1.9	1.22	6.0	1.09	1.4	0.82	17.0	1.37
22	7.9	1.79	1.9	1.11	6.3	0.98	1.5	0.91	17.6	1.51
23	7.7	1.78	2.2	1.11	6.7	0.98	1.5	1.01	18.2	1.54
24	8.0	1.79	2.2	1.13	7.1	1.12	1.5	1.03	18.8	1.63
25	8.0	1.65	2.3	1.09	7.4	1.08	1.7	1.12	19.4	1.77
26	7.8	1.66	2.6	1.09	7.9	1.12	1.7	1.11	20.0	1.86
27	7.9	1.77	2.8	1.16	8.3	1.16	1.6	1.03	20.6	1.86
28	7.6	1.75	3.1	1.16	8.8	1.15	1.8	1.00	21.2	1.80
29	8.1	2.19	2.9	1.40	9.0	1.15	1.8	1.09	21.8	1.84
30	8.2	2.31	3.0	1.42	9.4	1.13	1.9	1.07	22.5	1.93
31	8.8	2.57	2.9	1.64	9.6	1.09	1.8	1.03	23.2	1.90
32	9.4	2.50	2.7	1.68	9.9	1.07	1.9	0.95	23.9	1.69
33	9.5	2.42	2.8	1.64	10.3	1.09	1.9	0.94	24.5	1.72
34	9.2	2.31	3.1	1.64	10.8	1.07	1.9	0.91	24.9	1.83
35	9.1	2.47	3.2	1.72	11.2	1.13	1.8	0.96	25.3	1.93
36	9.2	2.62	3.3	1.78	11.6	1.10	1.7	1.05	25.8	2.08
37	9.2	2.49	3.4	1.80	12.0	1.23	1.7	1.14	26.3	2.07
38	9.5	2.56	3.3	1.82	12.3	1.32	1.6	1.09	26.8	2.06
39	9.3	2.62	3.6	1.82	12.8	1.33	1.6	1.05	27.1	2.11
40	10.9	2.95	2.7	1.95	12.9	1.52	1.6	1.08	28.1	1.99
41	11.0	3.01	2.6	1.89	13.2	1.48	1.5	1.19	28.4	2.18
42	11.2	2.83	2.5	1.72	13.5	1.29	1.6	1.21	28.8	2.24
43	11.6	2.94	2.3	1.71	13.8	1.46	1.5	1.26	29.2	2.15
44	12.7	2.80	1.6	1.40	13.8	1.24	1.5	1.19	29.8	2.15
45	12.8	2.12	1.2	1.10	13.8	1.29	1.6	1.19	29.4	2.11

Coordinated Launch Baseline Service Times. The means and standard deviation apply to Figure 5. Each row corresponds to a column. The GMTI, SAR, analyst, and decide means and standard deviations correspond to the height of each stacks in the figure, while the total corresponds to the total height of each column.

Order in which system completes TEL processing	95% Confidence interval for expected change in MOE (average remaining dwell time) between altered and baseline systems (MOE altered system - MOE baseline)
1	[1.0, 1.5]
2	[0.8, 2.0]
3	[1.3, 2.5]
4	[1.3, 2.6]
5	[0.8, 3.0]
6	[0.8, 2.8]
7	[0.2, 2.4]
8	[1.3, 3.6]
9	[- 0.5, 2.0]
10	[1.8, 3.8]
11	[0.8, 2.8]
12	[- 0.9, 1.6]
13	[2.0, 4.6]
14	[0.7, 3.0]
15	[1.5, 3.9]
16	[1.0, 3.5]
17	[0.4, 3.2]
18	[0.7, 3.6]
19	[0.2, 3.1]
20	[1.5, 4.1]
21	[1.2, 3.7]
22	[0.3, 3.2]
23	[1.3, 4.1]
24	[0.8, 3.1]
25	[0.9, 3.4]
26	[- 0.5, 2.3]
27	[1.2, 4.2]
28	[- 0.4, 2.3]
29	[0.4, 3.2]
30	[0.7, 3.7]
31	[0.7, 2.6]
32	[1.7, 4.2]
33	[1.7, 4.1]
34	[0.9, 3.0]
35	[0.4, 2.9]
36	[0.8, 3.2]
37	[0.8, 2.5]
38	[1.7, 3.7]
39	[- 0.1, 2.2]
40	[1.6, 3.8]
41	[0.7, 3.0]
42	[0.2, 2.5]
43	[1.4, 2.8]
44	[1.0, 2.7]
45	[1.4, 2.1]

95% Confidence Intervals for the Expected Change in Mean Remaining Dwell Times between the Baseline and Track-While-Scan CONOPS for Coordinated TBM Launches. The confidence intervals apply to Figure 6. Each row corresponds to a column in the Figure.

order in which system completes TEL processing	95% confidence intervals for expected change in MOE (average processing time) between altered and baseline systems (MOE baseline sytem - MOE altered system)		
	GMTI	SAR	Analyst
1	[1.0, 1.5]	[0.0, 0.0]	[0.0, 0.0]
2	[1.1, 1.6]	[0.1, 0.2]	[0.0, 0.2]
3	[1.2, 1.8]	[0.1, 0.2]	[- 0.1, 0.1]
4	[1.4, 2.1]	[0.1, 0.3]	[- 0.2, 0.1]
5	[1.6, 2.4]	[0.2, 0.4]	[- 0.5, 0.0]
6	[1.3, 2.2]	[0.3, 0.6]	[- 0.5, 0.0]
7	[1.5, 2.5]	[0.3, 0.6]	[- 0.7, - 0.1]
8	[1.8, 2.9]	[0.3, 0.7]	[- 1.0, - 0.4]
9	[1.8, 2.6]	[0.4, 0.7]	[- 1.1, - 0.5]
10	[1.7, 2.7]	[0.5, 0.9]	[- 1.2, - 0.6]
11	[2.2, 3.2]	[0.3, 0.8]	[- 1.5, - 0.9]
12	[2.0, 3.3]	[0.3, 0.9]	[- 1.5, - 0.9]
13	[2.2, 3.4]	[0.4, 0.9]	[- 1.7, - 1.1]
14	[2.3, 3.5]	[0.3, 0.9]	[- 1.9, - 1.3]
15	[2.2, 3.6]	[0.4, 1.0]	[- 2.1, - 1.5]
16	[3.0, 4.5]	[0.0, 0.8]	[- 2.4, - 1.8]
17	[2.9, 4.4]	[0.1, 0.9]	[- 2.4, - 1.9]
18	[3.5, 5.0]	[- 0.1, 0.7]	[- 2.7, - 2.1]
19	[3.5, 5.1]	[- 0.1, 0.7]	[- 2.9, - 2.2]
20	[3.7, 5.1]	[- 0.1, 0.7]	[- 2.9, - 2.3]
21	[4.2, 5.7]	[- 0.3, 0.5]	[- 3.2, - 2.5]
22	[4.4, 5.8]	[- 0.5, 0.4]	[- 3.4, - 2.7]
23	[4.1, 5.5]	[- 0.3, 0.6]	[- 3.4, - 2.7]
24	[4.4, 5.8]	[- 0.4, 0.5]	[- 3.4, - 2.9]
25	[4.6, 6.0]	[- 0.5, 0.5]	[- 3.5, - 3.0]
26	[4.3, 5.6]	[- 0.3, 0.7]	[- 3.5, - 3.0]
27	[4.3, 5.7]	[- 0.2, 0.8]	[- 3.6, - 3.0]
28	[4.1, 5.4]	[- 0.1, 0.9]	[- 3.6, - 3.0]
29	[4.6, 6.2]	[- 0.5, 0.7]	[- 3.8, - 3.2]
30	[4.3, 6.1]	[- 0.5, 0.8]	[- 3.8, - 3.3]
31	[4.9, 7.0]	[- 0.9, 0.6]	[- 4.0, - 3.4]
32	[5.5, 7.5]	[- 1.2, 0.2]	[- 4.2, - 3.7]
33	[5.7, 7.5]	[- 1.2, 0.2]	[- 4.3, - 3.8]
34	[5.4, 7.1]	[- 1.0, 0.4]	[- 4.3, - 3.8]
35	[5.1, 7.1]	[- 0.9, 0.5]	[- 4.4, - 3.8]
36	[5.2, 7.2]	[- 0.9, 0.4]	[- 4.4, - 3.8]
37	[5.5, 7.4]	[- 1.0, 0.4]	[- 4.5, - 3.9]
38	[5.5, 7.5]	[- 1.2, 0.2]	[- 4.6, - 4.0]
39	[5.4, 7.3]	[- 0.9, 0.5]	[- 4.6, - 4.0]
40	[6.9, 9.1]	[- 1.7, - 0.4]	[- 5.1, - 4.4]
41	[7.2, 9.4]	[- 1.9, - 0.5]	[- 5.2, - 4.5]
42	[7.1, 9.3]	[- 2.1, - 0.5]	[- 5.3, - 4.7]
43	[7.3, 9.6]	[- 2.1, - 0.6]	[- 5.5, - 4.9]
44	[8.6, 10.8]	[- 2.5, - 1.0]	[- 6.0, - 5.4]
45	[8.9, 10.6]	[- 2.0, - 0.9]	[- 6.5, - 5.8]

95% Confidence Intervals for the Expected Change in Mean Service Time (minutes) between the Baseline and Track-While-Scan CONOPS for Coordinated TBM Launches. The confidence intervals apply to Figure 7. Each row corresponds to one set of three columns in the figure.

order in which system completes TEL processing	95% confidence intervals for expected change in MOE (decision and mensuration processing time) between altered and baseline system
	(MOE baseline system - MOE altered system)
1	[0.0, 0.0]
2	[0.0, 0.2]
3	[0.0, 0.2]
4	[0.0, 0.2]
5	[0.0, 0.2]
6	[0.0, 0.2]
7	[0.0, 0.1]
8	[0.0, 0.1]
9	[0.0, 0.0]
10	[0.0, 0.0]
11	[0.0, 0.0]
12	[0.0, 0.0]
13	[0.0, 0.0]
14	[0.0, 0.0]
15	[0.0, 0.0]
16	[0.0, 0.0]
17	[0.0, 0.0]
18	[0.0, 0.0]
19	[0.0, 0.0]
20	[0.0, 0.0]
21	[0.0, 0.0]
22	[0.0, 0.0]
23	[0.0, 0.0]
24	[0.0, 0.0]
25	[0.0, 0.0]
26	[0.0, 0.0]
27	[0.0, 0.0]
28	[0.0, 0.0]
29	[0.0, 0.0]
30	[0.0, 0.0]
31	[0.0, 0.0]
32	[0.0, 0.0]
33	[0.0, 0.0]
34	[0.0, 0.0]
35	[0.0, 0.0]
36	[0.0, 0.0]
37	[0.0, 0.0]
38	[0.0, 0.0]
39	[0.0, 0.0]
40	[0.0, 0.0]
41	[0.0, 0.0]
42	[0.0, 0.0]
43	[0.0, 0.0]
44	[0.0, 0.0]
45	[0.0, 0.0]

95% Confidence Intervals for the Expected Change in the Mean Decision and Mensuration Service Times between the Baseline and Track-While-Scan CONOPS for Coordinated TBM Launches. These results are not included in Figure 7 because all of the 95% confidence intervals contain zero; changes in the mean times to make a decision and mensurate coordinates are not statistically significant between the baseline and track-while-scan models.

TEL number	stop			dwell time		
	mean stop time (min)	std error of mean	std dev	mean dwell time (min)	std error of mean	std dev
1	0.0	0.00	0.00	30.0	0.89	4.88
2	2.1	0.37	2.00	25.4	0.61	3.34
3	2.8	0.37	2.05	23.4	0.57	3.10
4	3.5	0.37	2.03	23.3	0.53	2.89
5	4.3	0.41	2.24	22.4	0.63	3.45
6	4.9	0.40	2.20	21.8	0.49	2.67
7	5.5	0.40	2.17	20.1	0.53	2.92
8	6.1	0.41	2.25	19.0	0.49	2.70
9	6.8	0.40	2.19	18.2	0.54	2.98
10	7.1	0.41	2.25	18.4	0.47	2.59
11	7.6	0.43	2.35	17.1	0.52	2.82
12	8.1	0.44	2.40	16.7	0.36	1.94
13	8.8	0.44	2.44	16.1	0.54	2.95
14	9.7	0.45	2.47	15.1	0.29	1.57
15	10.6	0.44	2.39	13.2	0.38	2.07

Coordinated Launch Stop and Dwell Time Standard Deviations for Baseline Model. The means and measures of dispersion apply to Figure 8. Each row corresponds to height of a column and its placement along x-axis in the Figure.

order in which system processes TELs	mean remaining dwell time (min)	std error of mean	95% confidence interval for mean remaining dwell time
1	25.4	0.80	[23.7, 27.0]
2	22.0	0.65	[20.7, 23.4]
3	20.2	0.65	[18.8, 21.5]
4	18.5	0.52	[17.4, 19.6]
5	18.0	0.65	[16.6, 19.3]
6	16.3	0.62	[15.1, 17.6]
7	16.4	0.55	[15.2, 17.5]
8	13.8	0.54	[12.7, 14.9]
9	13.4	0.54	[12.3, 14.5]
10	11.2	0.46	[10.3, 12.2]
11	11.0	0.53	[9.9, 12.1]
12	11.1	0.53	[10.0, 12.2]
13	9.0	0.56	[7.9, 10.2]
14	8.7	0.49	[7.7, 9.7]
15	7.1	0.59	[5.9, 8.3]
16	6.7	0.71	[5.2, 8.1]
17	6.2	0.60	[5.0, 7.4]
18	5.2	0.56	[4.1, 6.4]
19	4.5	0.54	[3.4, 5.7]
20	3.8	0.58	[2.6, 5.0]
21	3.0	0.64	[1.6, 4.3]
22	2.1	0.44	[1.2, 3.0]
23	0.7	0.54	[- 0.4, 1.8]
24	1.4	0.56	[0.2, 2.5]
25	-0.7	0.60	[- 1.9, 0.6]
26	-1.3	0.55	[- 2.4, - 0.1]
27	**-3.1**	**0.54**	[- 4.2, - 2.0]
28	**-3.1**	**0.53**	[- 4.2, - 2.0]
29	**-3.9**	**0.63**	[- 5.2, - 2.6]
30	**-5.2**	**0.61**	[- 6.4, - 3.9]
31	**-5.2**	**0.54**	[- 6.3, - 4.1]
32	**-7.3**	**0.54**	[- 8.4, - 6.1]
33	**-7.7**	**0.50**	[- 8.8, - 6.7]
34	**-7.4**	**0.49**	[- 8.4, - 6.5]
35	**-8.3**	**0.54**	[- 9.4, - 7.2]
36	**-9.4**	**0.54**	[- 10.5, - 8.3]
37	**-9.9**	**0.50**	[- 10.9, - 8.8]
38	**-11.1**	**0.52**	[- 12.1, - 10.0]
39	**-11.5**	**0.36**	[- 12.2, - 10.8]
40	**-12.5**	**0.55**	[- 13.6, - 11.3]
41	**-13.0**	**0.49**	[- 14.0, - 12.0]
42	**-13.5**	**0.45**	[- 14.4, - 12.6]
43	**-14.8**	**0.39**	[- 15.6, - 14.0]
44	**-15.7**	**0.44**	[- 16.6, - 14.8]
45	**-17.1**	**0.40**	[- 17.9, - 16.2]

TEL Remaining Dwell Times for Coordinated TBM Launch Baseline Model. The means, standard errors, and confidence intervals apply to Figure 9. Each row corresponds to a column in the figure.

APPENDIX C. EXTRA IMAGE ANALYST RESULTS

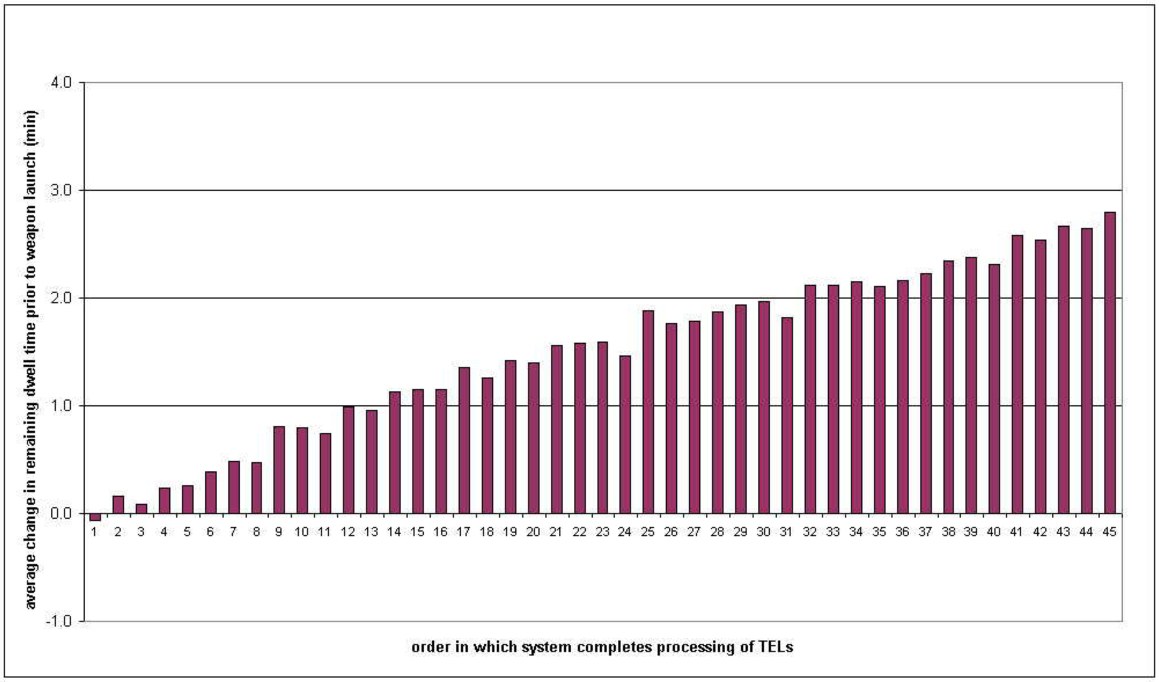
The baseline and track-while-scan results for both arrival processes indicate that waiting times in the analyst queue increase with the number of TELs in a launch wave. Therefore, one additional analyst is added in order to explore its impacts on system performance and processing times.

TEL dwell type	lognormal dwell time parameters in minutes (mean, stdev)	number of TELs in launch wave	mean number of TELs killed (MOE)	std error of MOE	95% confidence interval for expected difference between MOEs for altered and baseline systems (MOE altered system - MOE baseline system)
short	(10,2)	15	**2.88**	**0.16**	[- 0.02, 0.30]
		30	**2.86**	**0.14**	**[0.06, 0.30]**
		45	**3.06**	**0.14**	**[0.09, 0.39]**
	(10,10)	15	**4.38**	**0.23**	[- 0.03, 0.19
		30	**7.26**	**0.30**	**[0.07, 0.29]**
		45	**9.38**	**0.31**	**[0.07, 0.45]**
medium	(20,5)	15	**13.14**	**0.18**	**[0.28, 0.68]**
		30	**15.96**	**0.22**	**[0.52, 1.08]**
		45	**16.82**	**0.21**	**[0.50, 1.02]**
	(20,20)	15	**8.20**	**0.24**	[- 0.03, 0.15]
		30	**13.94**	**0.29**	[- 0.04, 0.24]
		45	**17.58**	**0.20**	**[0.10, 0.38]**
long	(30,5)	15	**15.00**	**0.00**	[0.00, 0.00]
		30	**20.90**	**0.29**	**[0.84, 1.64]**
		45	**22.40**	**0.33**	**[1.04, 1.92]**
	(30,20)	15	**13.28**	**0.20**	[- 0.01, 0.13]
		30	**19.02**	**0.19**	[0.00, 0.24]
		45	**23.52**	**0.41**	**[0.59, 1.17]**

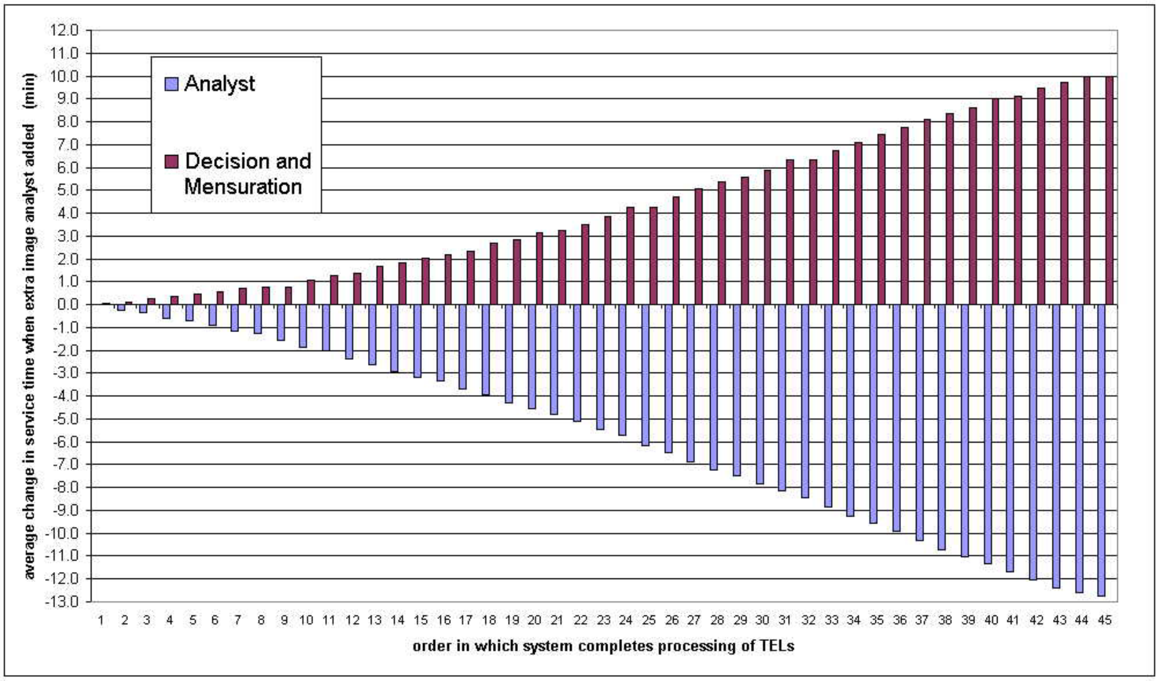
One Additional Image Analyst Baseline Results for Coordinated Launch TEL Arrival Process. Each mean and standard error of the MOE is based on 50 simulation replications using the lognormal parameters and the number of TELs in the second and third columns as inputs. The 95% confidence intervals are for the paired difference between the 2-image analyst and 1-image analyst MOEs. There is no improvement or degradation for the case consisting of 15 long-dwell TELs with the lognormal (30,5) dwell time distribution because both the baseline and track-while-scan systems were able to kill every TEL in the launch wave in every replication.

Most of the 95 percent confidence intervals for the paired difference between the 2-image analyst and single image analyst MOEs in the above table show that increasing the number of image analysts from one to two in the baseline model results in less than 2 additional mean number of TELs kills. The increases in the means of the number of TELs killed are not significant from a practical standpoint. The following figures show the impacts of the additional analyst and explain why the system does not perform as well as might be expected.

The first figure below illustrates that mean remaining TEL dwell times do not increase substantially when an another image analyst is added to the baseline model, while the second figure shows that reductions gained in the image analysis phase of the kill chain are mostly negated by increased decision and mensuration service times. These results imply that reductions in the decision and mensuration phase need to be addressed.



Average Change in Mean Remaining TEL Dwell Time, Prior to Engagement, between the Baseline Models with One and Two Image Analysts. The ordering of the columns corresponds to the order in which 45 lognormal (20,5) medium-dwell TELs are engaged by the TCS system. The height of each column is the average difference between the single image analyst and two image analysts baseline remaining dwell times, before the shooter platform launches its weapon, for the coordinated launch case and 30 replications. For example, the 45th TEL engaged by both systems has a mean of about three additional minutes of remaining dwell time, on average, in the multiple image analyst model before the shooter platform is able to fire its weapon.



Average Change in Mean TEL Processing Times Between the Single Image Analyst and Two Image Analysts Baseline Models for Coordinated TBM Launches. This chart should be read as 45 sets of two columns each. The arrangement of the sets along the x-axis corresponds to the order in which 45 lognormal (20,5) medium-dwell TELs are engaged by the TCS models. The first and second columns in each set are the average changes in service times, based on 30 replications, for the image analysis and decision and mensuration phases of the kill chain, respectively (Note that the GMTI and SAR columns are omitted because they are unaffected). Column heights are negative if the two image analysts average service times are less than the single analyst baseline. For example, the 45th TEL engaged by both systems spends on average 13 minutes less in the image analysis phase and 10 minutes more in the decision and mensuration phase for the two image analysts model when compared to the baseline.

APPENDIX D. ORDER STATISTICS

Let Y_r be the r$^{\text{th}}$ order statistic for a random sample of size N from a population with probability density function $f(x)$ and cumulative distribution function $F(x)$ (reference 9). The probability density of Y_r is given by, $g_r(y_r) = \dfrac{n!}{(r-1)!(n-r)!}\left[F(y_r)\right]^{r-1} f(y_r)\left[1-F(y_r)\right]^{n-r}$ for $-\infty < y_r < \infty$. Assume TELs are engaged in descending order of dwell time. The dwell time of the first TEL engaged has the same distribution as that of the largest order statistic of the dwell times; the dwell time of the last TEL engaged has the same distribution as that of the first order statistic of the dwell times.

The expected dwell time of the $(N+1-r)^{\text{th}}$ engaged TEL is given by $\mathrm{E}[Y_r] = \int_{-\infty}^{\infty} y.g_r(y)\,\mathrm{d}y$. This integral is evaluated using a simple right-endpoint approximation (reference 10). Since the minimum value of a lognormal distribution is zero, we choose an interval, [0,b] with b sufficiently large in which to evaluate the integral. For the dwell time distributions to which this technique is applied, b = 60 minutes is large enough; the cumulative distributions of all order statistics is approximately 1. Let $w = 0.01$ minutes be the subinterval width in which to partition [0,b]. It follows that the number of subintervals for approximation is given by $m = \dfrac{b}{w}$. Let $y_i = iw$ be the right endpoint of subinterval i. The approximation to the expected dwell time of the $(N+1-r)^{\mathrm{th}}$ engaged TEL is then given by $\mathrm{E}[Y_r] = \int_{-\infty}^{\infty} y.g_r(y_r)\,\mathrm{d}y \approx \sum_{i=1}^{m} y_i g_r(y_i) w = w\sum_{i=1}^{m} y_i g_r(y_i)$.

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